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HYFIRE II
FUSION/HIGH-TEMPERATURE ELECTROLYSIS CONCEPTUAL-DESIGN STUDY

ANNUAL REPORT

J.A. FILLO, EDITOR

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J.A. Fillo, Editor

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Upton, New York 11973

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EXECUTIVE SUMMARY

As in the previous HYFIRE design study, the current study focuses on coupling a Tokamak fusion reactor with a high-temperature blanket to a High-Temperature Electrolyzer (HTE) process to produce hydrogen and oxygen. Scaling of the STARFIRE reactor to allow a blanket power to 6000 MW(th) is also assumed. The primary difference between the two studies is the maximum inlet steam temperature to the electrolyzer. This temperature is decreased from ~1300° to ~1150°C, which is closer to the maximum projected temperature of the Westinghouse fuel cell design. The process flow conditions change but the basic design philosophy and approaches to process design remain the same as before. Westinghouse assisted in the study in the areas of systems design integration, plasma engineering, balance-of-plant design, and electrolyzer technology.

The guidelines for this study were essentially similar to those used in the development of the STARFIRE reference Tokamak reactor design. The final HYFIRE plant embodiment was to represent the tenth-of-a-kind first generation plant. STARFIRE technology assumptions and design features were to be used to the extent possible to permit concentration on high-temperature blanket and balance-of-plant design issues.

In addition to the requirement for tritium self-sufficiency, an important ground rule for this initial series of studies was that hydrogen would be the only product produced for sale. Thus, the electrical generation equipment and the overall power conversion process would be sized to exactly provide the electrical energy required to operate the Tokamak, electrolysis plant, and balance-of-plant systems.

A complete process flow sheet has been developed for the system coupling the high-temperature blanket to the high-temperature electrolysis and electrical power generation subsystems, and material flow and energy balances accomplished through the development of a digital computer code to represent the overall cycle.

The overall plant can be thought of as having four principle process circuits:

1. the low-temperature water loop which extracts heat from the front wall of the blanket elements;
2. the helium loop;
3. the steam-hydrogen loop which provides the dual function of electricity generation and hydrogen production; and
4. the waste oxygen circuit.

The steam-hydrogen loop is by far the most involved.

Low-temperature water which extracts heat from the first wall and high-temperature helium are used to raise steam for the high-pressure turbine which is then used to make electricity to operate the electrolyzers, fusion reactor, and balance-of-plant.

Since only about 10% of the steam is converted to hydrogen per pass, some effort is required to separate and recycle the steam so that product hydrogen can meet purity specifications. The steam is condensible at normal ambient conditions and the hydrogen is not. Thus, the recovery scheme involves cooling the mixture followed by condensation of the steam and subsequent phase separation. To achieve a product hydrogen steam in excess of 99% purity, an eight-stage condenser/compressor string is used.

Table I summarizes key cycle parameters associated with the high-temperature design point. The thermal power to the electrolyzers is ~30% of the total power required to operate the electrolyzers for electrolysis of steam. The overall efficiency to produce hydrogen from fusion energy is 50%.

In summary, the HYFIRE studies to date have investigated a number of technical approaches for using the thermal energy produced in a high-temperature Tokamak blanket to provide the electrical and thermal energy required to drive a high-temperature water electrolysis process. Current emphasis has been on two design points, one consistent with electrolyzer peak inlet temperatures of ~1300°C, which is an extrapolation of present experience, and one consistent with a peak electrolyzer temperature of 1100°C. This latter condition is based on current laboratory experience with high-temperature solid electrolyte fuel cells.

The Tokamak driver for HYFIRE is based on the STARFIRE reference commercial fusion power plant design. A reference blanket design has been selected, incorporating modules designed to produce high-temperature steam and modules designed to breed tritium and provide process heat. Process design and plant layout has been completed; component cost and plant economics studies show hydrogen production costs to be $7.14/MBtu. This cost compares competitively with the price of hydrogen generated from natural gas and coal which ranges from $4.00 to $7.00. In addition, the technical integration of fusion and high-temperature electrolysis appears to be feasible and that overall hydrogen production efficiencies of 50 to 55% seem possible.

TABLE I

SUMMARY OF HYFIRE PLANT PARAMETERS

Gross Blanket Thermal Power, MW(th)	6000	Blanket
Steam Exit Temperature, °C	1142	Blanket
Helium Exit Temperature, °C	732	
Pressure Turbine Inlet Pressure, °C	538	High
Pressure Turbine Inlet Pressure, MPa	8.50	High
Pressure Turbine Inlet Temperature, °C	474	Low
Pressure Turbine Inlet Temperature, MPa	3.38	Low
Electrical Power to Electrolyzers, MW(e)	1620	
Thermal Power to Electrolyzers, MW(th)	650	
Production: Metric Ton/Day	1580	
kg/hr	65830	
Fusion Power to Hydrogen Conversion Efficiency, %	50	

1.0 INTRODUCTION

As in the previous[1] HYFIRE design study, the current study focuses on coupling a Tokamak fusion reactor with a high-temperature blanket to a High-Temperature Electrolyzer (HTE) process to produce hydrogen and oxygen. Scaling of the STARFIRE reactor to allow a blanket power to 6000 MW(th) is also assumed. The primary difference between the two studies is the maximum inlet steam temperature to the electrolyzer. This temperature is decreased from ~1300° to ~1150°C, which is closer to the maximum projected temperature of the Westinghouse fuel cell design. The process flow conditions change but the basic design philosophy and approaches to process design remain the same as before.

The current report does not go into as much detail as Ref. (1). For example, since the blanket design does not change except for the thermal hydraulics (and thermo-mechanical aspects of the design) because of the lower steam temperatures, a section on blanket design does not appear. In some cases, where information has been updated or new work has been carried out, sections have been repeated and expanded. As previously, Westinghouse assisted in the study in the areas of systems design integration, balance-of-plant design, electrolyzer technology, and systems costing.

Coverage of the basic contents of the report are identified in the following sections. Section 2 covers the HTE modeling and reference design. Section 3 discusses the plant process and power conversion design. Section 4 covers plant integration, and Section 5 is a detailed accounting of plant economics.

2.0 HIGH-TEMPERATURE ELECTROLYZER DESIGN

This Section provides a summary of the principles of high-temperature electrolysis and descriptions of the designs of the high-temperature electrolyzer (HTE) and the associated synfuel plant.

2.1 Electrolyzer Design Fundamentals

In a previous report[1] the fundamentals of high-temperature electrolysis were discussed. Some of this information has been updated.

This section briefly describes the principles of the electrolyzer. A schematic electrolysis cell is shown in Fig. 2.1-1, using a conducting solid electrolyte. At the cathode, water is reduced to oxygen ions and hydrogen. The hydrogen mixes with the steam while the oxygen ions move across the electrolyte via a vacancy migration mechanim to react at the anode to form oxygen.

The arrows in Fig. 2.1-1 indicate the direction of current flow for the high-temperature solid oxide systems. A schematic of the Westinghouse fuel cell is shown in Fig. 2.1-2. The flow of current is along the length of the tube. If the cells are too long, the large resistances would result in large voltage losses. This consideration in the design of the stacks of cells leads to narrow cells in series. This design also serves as the basis for the HTE since an electrolyzer is a fuel cell operating in reverse. Electrolyte resistance is a major cause of voltage losses. In order to reduce the resistance of the electrolyte (thin layers of electrodes), the electrolyte and interconnections are vapor-deposited on a porous support structure (in this case, a porous yttria-stabilized zirconia tube). This technique allows for an extremely thin support cell layer of about ~100 μm thick. In unsupported cell stacks, the electrolyte also serves as the mechanical structure and, therefore, could not be made

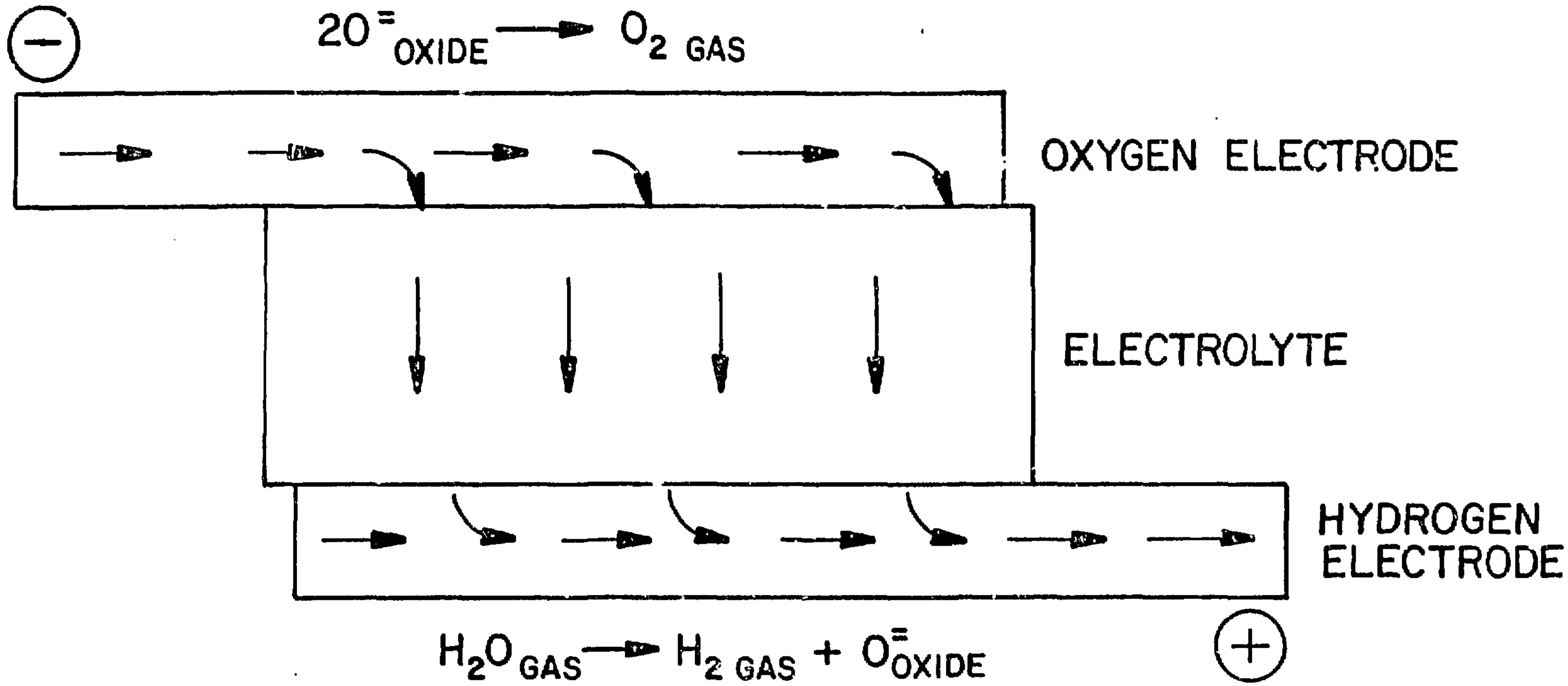


FIGURE 2.1-1

SCHEMATIC OF HIGH TEMPERATURE ELECTROLYSIS

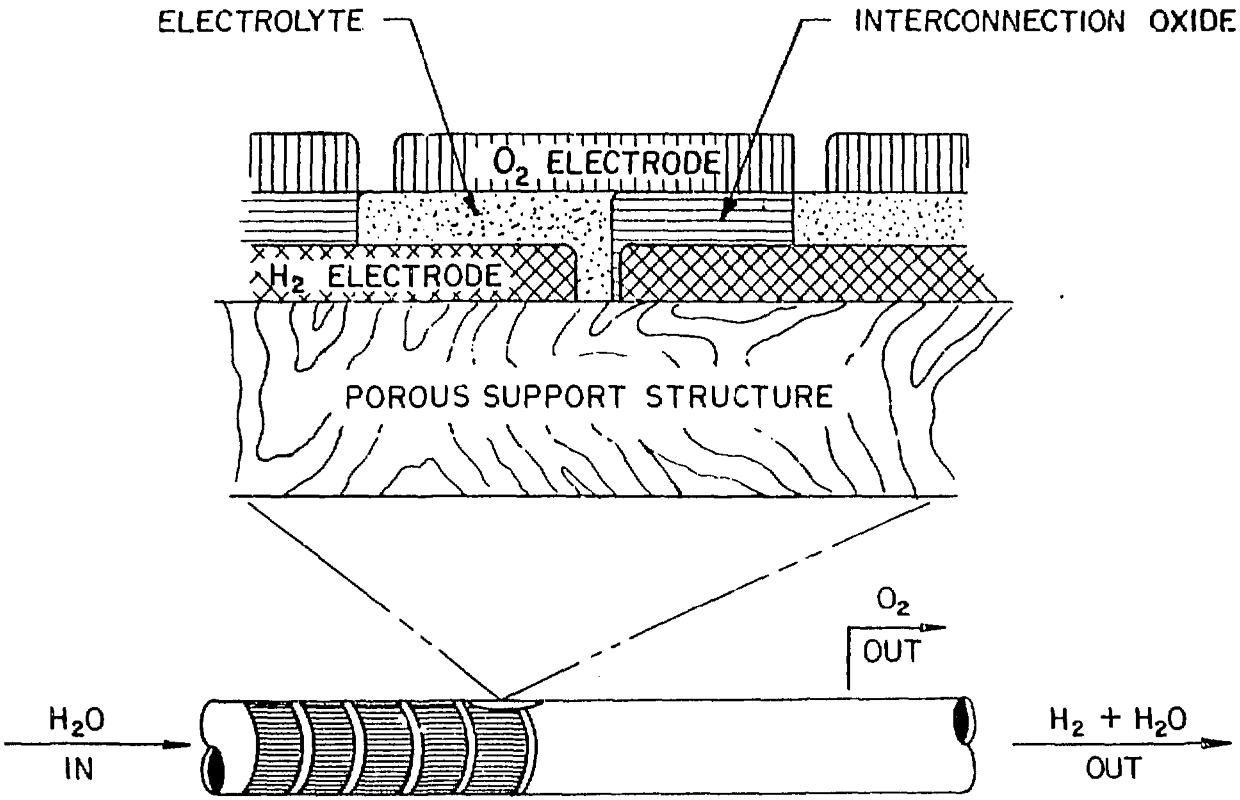


FIGURE 2.1-2

HTE CELL DESIGN
(WESTINGHOUSE FUEL CELL)

too thin because of strength limitations, but this is not the case in the current design.

The efficiency of the electrolyzer is a function of the voltage losses which increase the operating potential of the cells to values greater than that given by the Nernst Equation. The additional voltage required or overpotential arises from the resistances of all the components: the anode, cathode, electrolyte and interconnections between cells in the stack, and the kinetic limitations of the electrode reactions at the anode. These limitations depend on the diffusion of the water, hydrogen, or oxygen in the pores of the electrode structure, hence they depend on the electrode morphologies and materials. The resistances are established by physical properties, material resistivities, and thicknesses of the electrode, electrolyte, and interconnections.

The voltage losses increase the electrical energy required for electrolysis and as this energy is lost in the form of heat, less direct sensible heat must be supplied to the electrolyzer. The overall net result is an increased consumption of electrical energy and a reduction in plant efficiency. The electrical losses also increase with increasing cell current density, but increasing current density reduces the size of the plant and its capital costs for a particular hydrogen production rate. Therefore, a compromise must be struck.

2.2 Electrolyzer Tube and Vessel Designs

The design of an HTE occurs in two steps. The first defines the electrolyzer tube geometry and materials and establishes the performance characteristics of the electrolyzer tube; the second consists in design of the repetitive arrangement and assembly of thousands of the tubes within the HTE containment vessel. The definition of the electrolyzer tube materials and geometry follows the development work being conducted by Westinghouse on its high temperature solid oxide fuel cell that can reach hot spot temperatures of 1100°C. The electrolyzer tube geometry has two design options: One, construction of an electrolyzer tube as a single electrolyzer cell or as a multicell tube with the cells connected electrically in series along the length of the tube; and two, construction of the electrolyzer tube either to handle the steam-hydrogen flow on the inside of the tube (and the oxygen flow on the outside of the tube) or to handle the steam-hydrogen flow on the outside of the tube (and the oxygen flow on the inside of the tube). The construction of a series-connected multicell with the steam-hydrogen flow confined to the inside of the tube has been selected by Brookhaven National Laboratory (BNL) for the HTE design.

Three operating conditions must be defined for the electrolyzer: 1) the inlet steam temperature and with it the electrolyzer tube temperature profile; 2) the current density within the cells of the series-connected multicell tube; and 3) either the steam flow rate, which along with the above two conditions, determines the steam-to-hydrogen molal ratio or the molal ratio, which determines the steam flow rate.

A simple design procedure has been developed to predict the performance of a series-connected multicell tube that can reasonably be assumed to be isothermal at the mean temperature of the inlet and outlet streams. This design procedure is described in Appendix A. With the tube geometry, tube materials, tube temperature, and inlet steam-to-hydrogen molal ratio identified, the first step of the design establishes the variation of the R-factor (defined as the ratio of the electric energy added to the tube to the thermal energy added from the steam to the tube), and the variation of the tube voltage with parametric variation of the current density in the electrolysis cells. Such a parametric variation, shown in Fig. 2.2-1, is calculated for a typical tube geometry and with typical tube materials, as described in Appendix A.

Although Appendix A deals with the design option of oxygen inside the tube, the results can be applied with little error to the inverted tube geometry with the oxygen on the outside as used in the plant reference design. The electrolyte dimension used in the plant design is the same as that described in Appendix A. The important dimensions related to the plant tube geometry are the following:

Support Tube, i.d.	1.190 cm
Support Tube, o.d.	1.390 cm
Electrode, o.d.:	1.410 cm
Electrolyte, o.d.	1.418 cm
Oxygen Electrode, o.d.	1.558 cm
Length	156 cm

The second step of the design of the HTE consists of selecting a current density and with it the number of electrolyzer tubes needed to electrolyze the preselected design production rate of hydrogen.

A computer program (Appendix B) was developed to calculate the HTE tube performance with temperature varying along the length of the tube such that it follows the temperature profile of the steam-hydrogen stream. In addition, diffusion polarization values are included to describe more accurately the electrolyzer tube performance. The code assumes a series-connected multicell structure with the oxygen inside the tube.

In the HYFIRE Tokamak plant, there are twenty-eight electrolyzers, i.e., one electrolyzer for each blanket sector. This simplifies the headering system

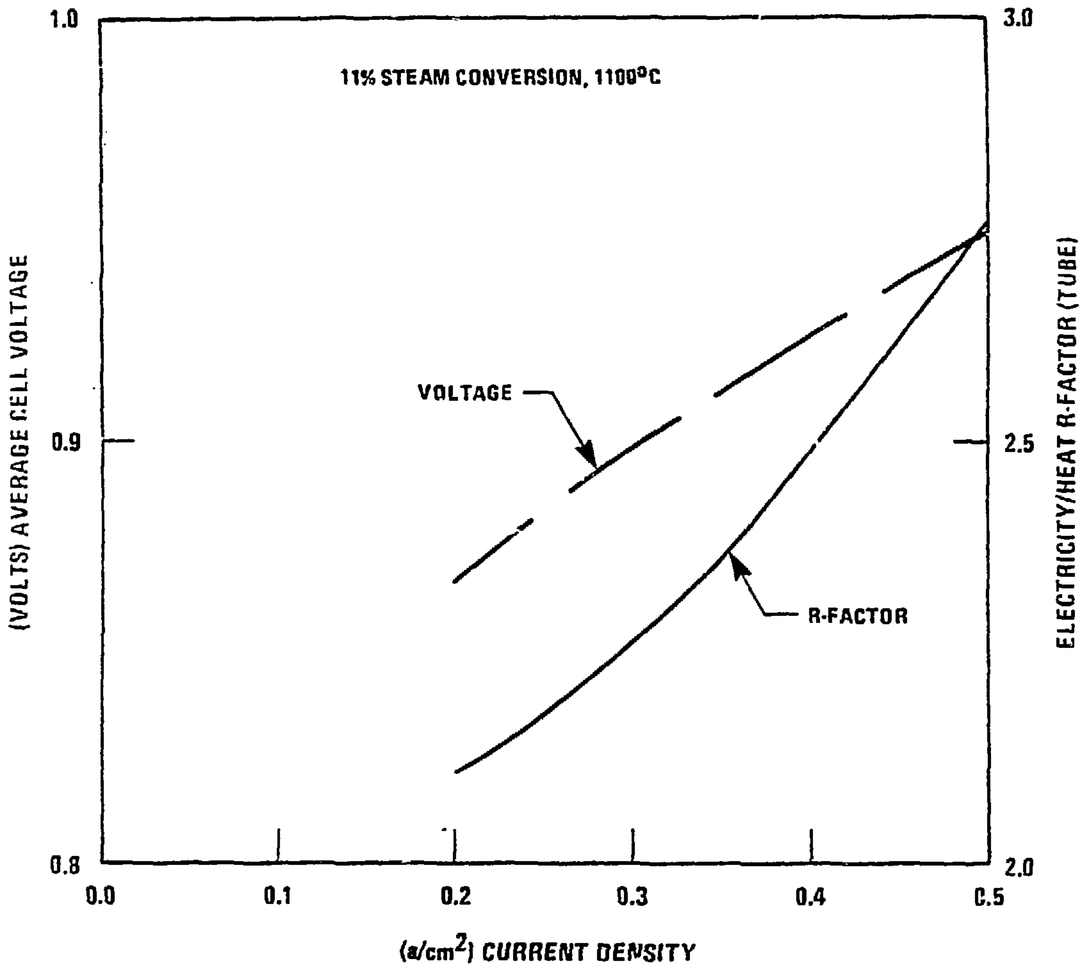


FIGURE 2.2-1

R-Factor for Tube and Average Cell Voltage vs. Cell Current Density and reduces the cost by providing common components. The electrolyzer assembly consists of tube sheets inserted in a cooled steel pressure vessel, internally insulated, which operates at ~30 atm. Steam is fed to the electrolyzer where water is reduced to hydrogen on one side of the electrolyte and oxygen is liberated on the other. Since only ~10% of the steam input is converted to hydrogen in a single pass, the steam exiting the electrolyzer vessel is a mixture of steam and hydrogen. At a later stage in the process, the steam is condensed to water, leaving behind hydrogen at virtually 100% purity. This is discussed in detail in Section 3.

The plant electrolyzer tubes are constructed as shown by the schematic in Fig. 2.2-2. A current density of 0.5 A/cm^2 in the electrolyte was used and it was assumed that 0.80 of the tube length was effective electrolyte. The thickness of the oxygen electrode was taken as 0.05 cm so that the diameter of the electrolyte is the tube o.d. minus 0.10 cm. The tubes are closed at one end and each end has a conduction oxide layer. At the closed end, the conducting surface oxide is in electrical contact with an oxide cap which passes through the insulation. The end of the cap is at a temperature where metal can be used in the oxidizing atmosphere. The metal continues the electrical path to a conducting plate at each end of the vessel. The plate, in turn, is connected to an insulated terminal through the pressure vessel. The open end of the electrolyte support tube with its conducting oxide is sealed into the tube sheet section with a conducting seal. The seal, in turn, makes contact with a conducting seal. The seal makes contact with a conducting oxide facing the tube sheet sections which are also sealed together with a conducting ceramic seal.

As Fig. 2.2-2 indicates, the steam entering the HTE is distributed from the central plenum through feed tubes. The feed tubes can be joined to tubes that

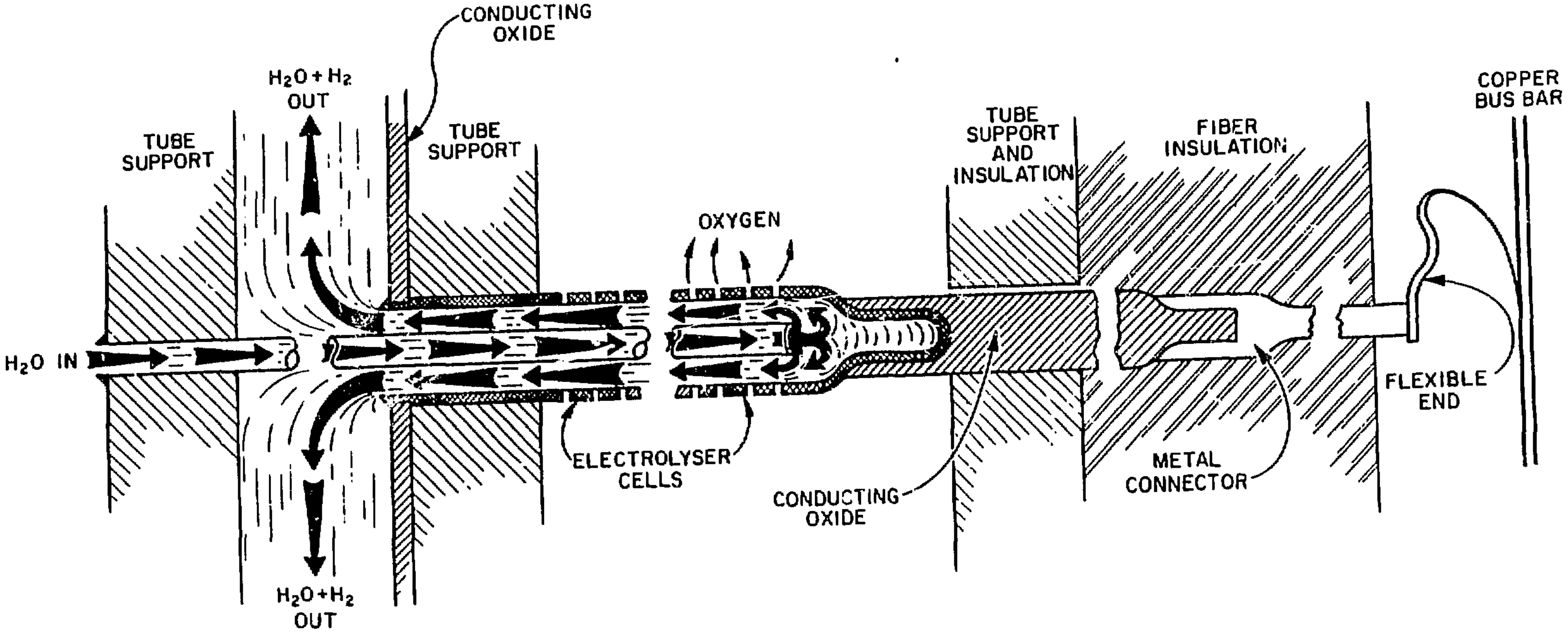


FIGURE 2.2-2

DETAILED CROSS-SECTION OF HTE CELL

are sealed together. A feed tube has spacers to center it in theelectrolyte tube and can support the outer tube at high temperatures if required. The feed tubes are centered within the electrolyte support tube. It then passes between the tube and feed tubes to the second plenum. During passage, the gas diffuses across the porous support tube to the cathode where it is electrolyzed to hydrogen and cooled by the endothermic reaction.

The two tube sheets which hold the feed tubes are the electrolyte support tubes, respectively. Both are constructed as interconnecting sections which are sealed together with a ceramic braze. A schematic of the tube sheet section is shown in Fig. 2.2-3, which consists of V-notched edges which fit into adjacent sections. The shapes of the sections are designed to conform with the ceramic insulation and support around the walls. A triangular tube spacing with a spacing to tube o.d. ratio of 1.25 was assumed.

Figure 2.2-4 is a cross section through an electrolyzer showing how the 1.5-meter-long tubes are arranged inside the vessel. The total hydrogen production of 1.45×10^5 lb/hr called for in the HYFIRE Tokamak process flow sheet with the electrical to thermal ratio, R, equal to 2.5 is obtained with 375,000 tubes in each of twenty-eight electrolyzers operating at a current density of 0.30 A/cm^2. The spacer tubes with a triangular pitched array have a center-to-center spacing of 1.73 cm which gives a clearance between tubes of .29 cm. A design with 0.50 A/cm^2 will have 225,360 tubes spaced 2.4 cm center-to-center but the electrolyzer will operate with R = 3.07 instead of 2.5 as called for in the process flow sheet. The diameter of the vessel is on the order of 6 m and the height is 15.9 m. Each central plena receives the high-temperature steam entering the HTE. Two adjacent plena collect the gas after electrolysis has

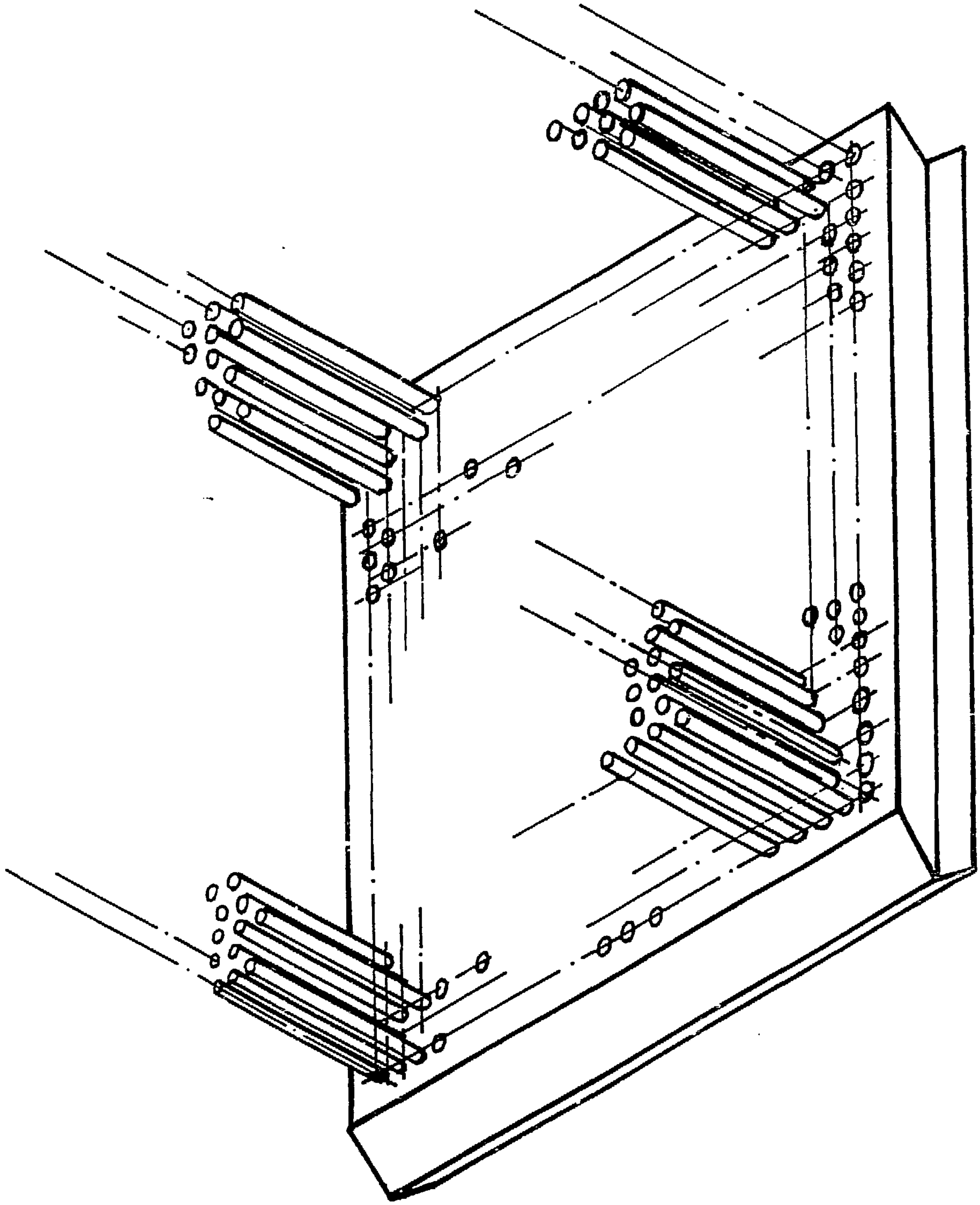


FIGURE 2.2-3

TUBE SHEET SECTION

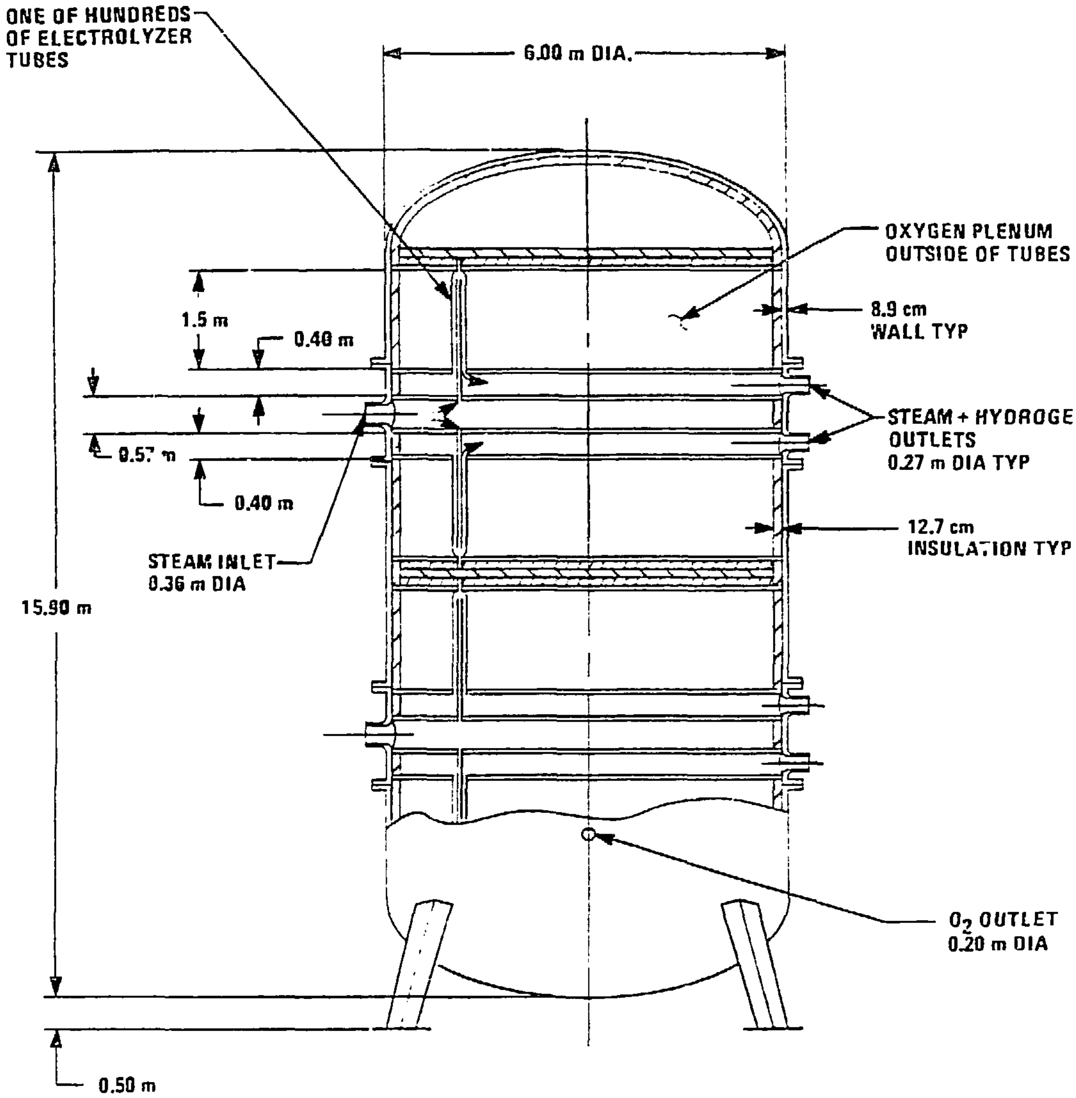


FIGURE 2.2-4

Cross-Section of Electrolyzer

taken place in the tubes. These are next to the large plena in which the oxygen is collected. The two end sections of the HTE unit are at low temperatures, and house electrical connections at the end of the electrolyte tubes.

A major factor in the design of the electrolyzers is the minimization of thermal stresses due to heating, cooling, and temperature cycling during operation. The outer cooled region of the containment vessel is held at virtually constant temperature at all times and will not experience any significant problem. Internal components, on the other hand, will experience temperature changes of over 1000°C and large dimensional changes when the HTE unit starts up from or shuts down to room temperature. The tubes, for example, are designed so that one end is fixed, with the other free to move to accommodate the dimensional changes.

3.0 PROCESS/POWER CYCLE

3.1 Reference Power Cycle Design

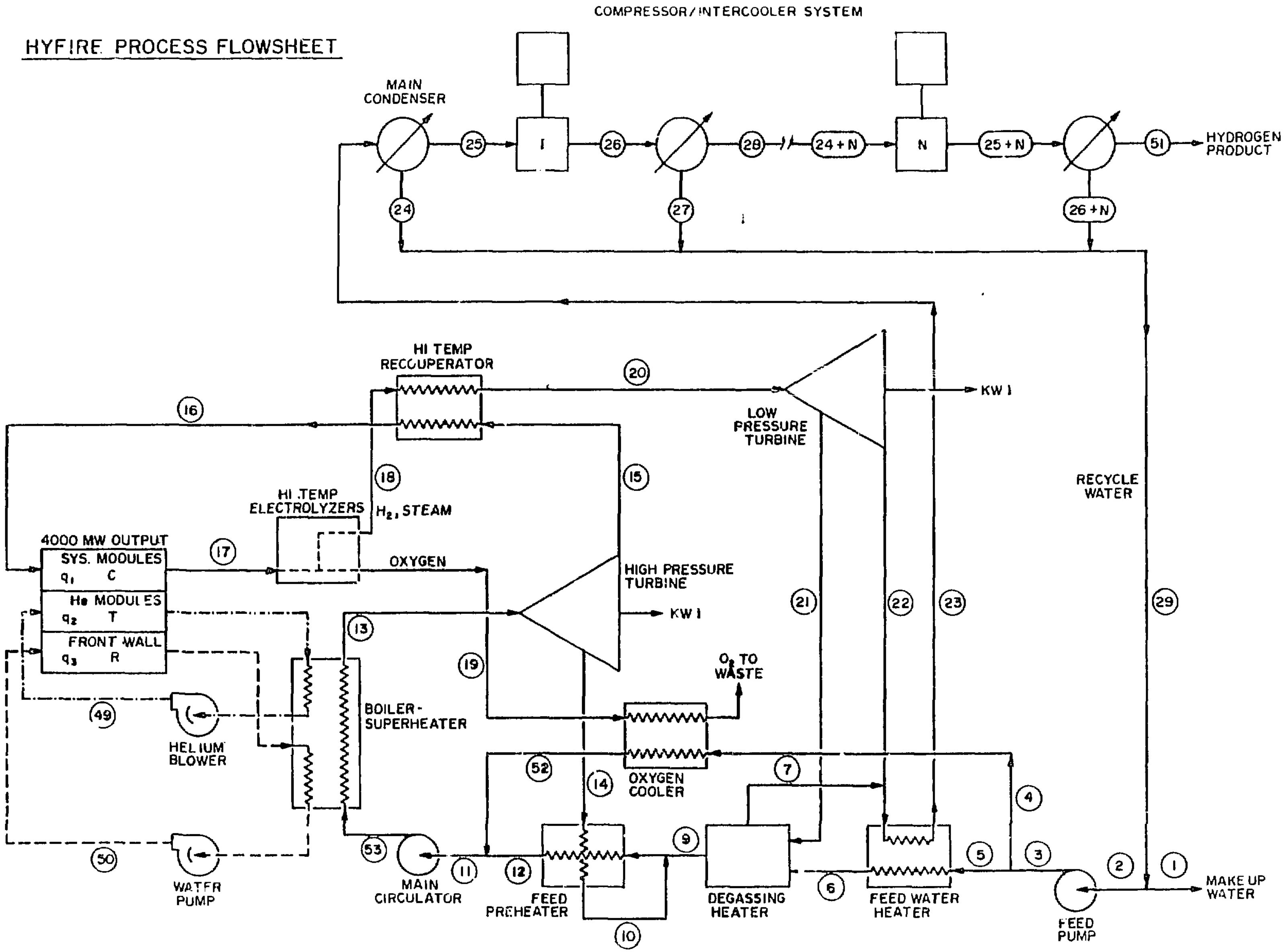
The high-temperature water electrolysis process in HYFIRE is intimately associated with the electrical power generation process. Both processes are shown on a single flow sheet, Fig. 3.1-1. The same water which flows through the power cycle flows through the electrolysis units. The design parameters have been balanced out so that for the entire plant, the only products (excluding fuel for the reactor) which cross plant boundaries are water and hydrogen.

A. Overall Energy Flow in HYFIRE

The HYFIRE process described in this report is capable of converting the fusion energy into thermochemical energy of hydrogen. The overall energy flow from the Tokamak blanket is shown in Fig. 3.1-2. The distribution of fusion energy to high-temperature steam modules or to helium modules is arbitrary and depends on the assumed coverage of the first wall by either type of module. Within both the high-temperature steam modules and the helium modules, the distribution of fusion energy to the relatively low-temperature first wall coolant or to the higher temperature regions depends on the neutronics of the module composition. The combination of these two effects is shown in Fig. 3.1-2, i.e., 39% of the total energy goes to the first wall and of the remainder, 44% goes to helium and 17% goes to high-temperature steam. This results in a blanket coverage of 38% for steam modules and 62% for helium modules.

The helium and first wall coolant together raise 638°C, 83 atm superheated steam in the specially designed boiler-superheater.

The intermediate pressure steam discharging from the HP turbine has its energy content augmented by the fusion energy which is deposited in the high-temperature region of the steam modules. Thus, a total of 11% of the



HYFIRE PROCESS FLOWSHEET
COMPRESSOR/INTERCOOLER SYSTEM
MAIN CONDENSER
HYDROGEN PRODUCT
HI TEMP RECCUPERATOR
LOW PRESSURE TURBINE
KW I
RECYCLE WATER
HI TEMP ELECTROLYZERS
H_2, STEAM
4000 MW OUTPUT
SYS. MODULES
He MODULES
FRONT WALL
OXYGEN
HIGH PRESSURE TURBINE
O_2 TO WASTE
BOILER-SUPERHEATER
HELIUM BLOWER
OXYGEN COOLER
WATER PUMP
MAIN CIRCULATOR
FEED PREHEATER
DEGASSING HEATER
FEED WATER HEATER
FEED PUMP
MAKE UP WATER

FIGURE 3.1-1

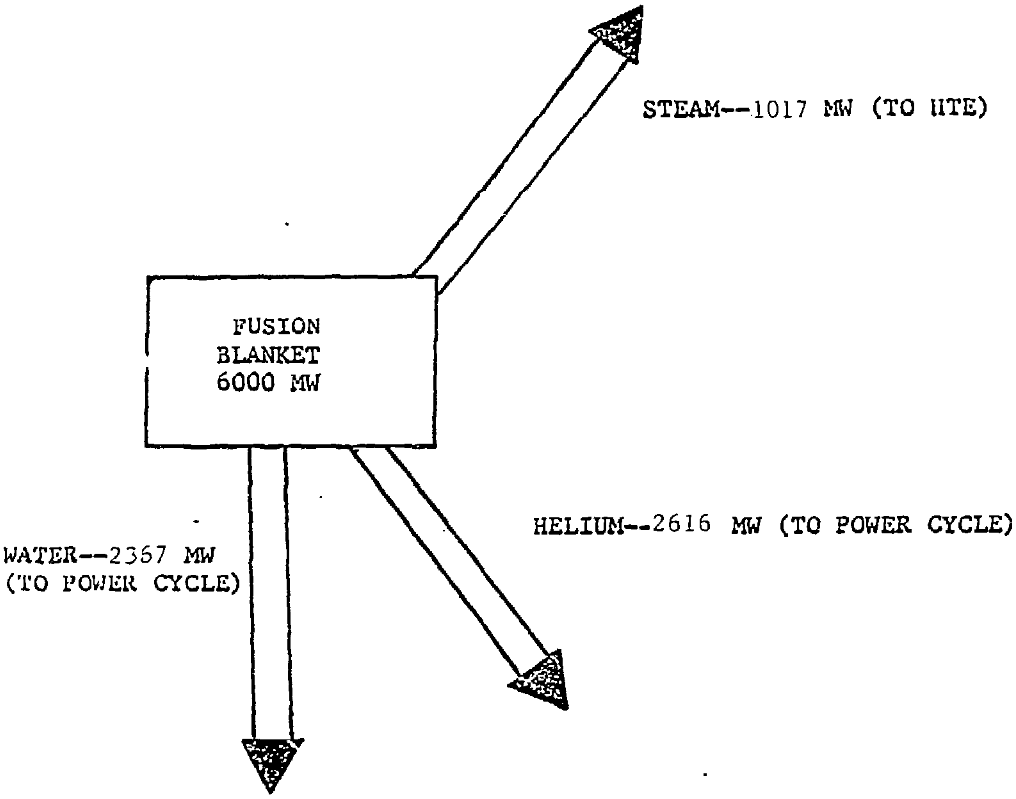


FIGURE 3.1-2 **OVERALL ENERGY FLOW**

fusion energy enters the high-temperature electrolysis cells where somewhat less than 650 MW(th) of the energy content of the inlet stream is required for the decomposition of 10% of the water into hydrogen and oxygen.

The effluent products of the HTE, namely, steam, hydrogen, and oxygen pass on to the remainder of the power generating cycle. In all, some 37% of the fusion energy is converted to electricity, the bulk of which is sent to the HTE to satisfy their electrical energy need. An assumed 150 MW(e) is recycled to the CTR for rf heating and the remainder of the electrical energy is required by the several pumps, blowers, and compressors as shown on the flow sheet. The electrical power to the primary helium circulator is high, having been calculated at 188 MW(e).

B. Point Design Process/Power Cycle Analysis

The overall process/power cycle flow sheet shown in Fig. 3.1-1 involves the conversion of fusion energy (thermal) to gaseous hydrogen via water electrolysis at the highest temperature possible consistent with the best technology and materials currently available. Since the plant is to generate its own electricity to run the electrolyzers as well as to satisfy all other electrical requirements (but with no net electricity for export), there is a requirement to provide steam generators, turbines, condensers, feed-water heaters, etc., that is, the usual components of a steam-electric power plant. From the point of view of the fusion reactor, there is the need to breed tritium which imposes restrictions on materials of construction for the blanket components as well as for process fluids, i.e., coolant streams. We have elected to satisfy these diverse requirements by designing the blanket with three distinctly different heat generation zones, each with its own process fluid and each with its own set of process parameters.

One zone which involves the first wall of all modules operates at the relatively modest temperature of 340°C (average) and is kept cool by this circulation of pressurized water at 193 atm. The pressurized water coolant from this zone is circulated through a steam generator in which 83 atm saturated steam is generated on the secondary side.

Another zone, which lies behind the first wall of the power modules is optimized for tritium breeding. This zone will operate at ~700°C and is cooled by pressurized (30 atm) helium which exchanges heat with a secondary helium stream (at ~70 atm) in small heat exchangers outboard of the blanket.

The third and final zone, which lies behind the first wall of the remaining steam-cooled blanket modules, is designed with the needs of the high-temperature electrolyzers in mind. This zone will operate in excess of 1000°C and serves to resuperheat relatively low pressure (30 atm) steam to ~1142°C before it goes into the electrolyzers. All of the heat from this zone of the blanket is used to provide the thermal energy required to dissociate water in the electrolyzers.

The overall plant can be thought of as having four principle process circuits:

1. the low-temperature water loop which extracts heat from the first wall of the blanket elements;
2. the helium loop;
3. the steam-hydrogen loop which provides the dual function of electricity generation and hydrogen production; and
4. the waste oxygen circuit.

The steam-hydrogen loop is by far the most involved.

To simplify plumbing between the electrolyzers and blanket, steam is transported from the blanket to the electrolyzers in a single pass. The conversion per pass through the entire cycle is approximately what was the conversion per pass with multiple recycle through a single HTE in the earlier design concept. The present design is somewhat less efficient but is probably somewhat more realistic.

Make-up water is added to recycled water and together they enter a train of feed-water preheaters for which suitable deionization facilities will be required. This water is heated to 142°C, by extraction streams taken from the various turbines, at which temperature it enters the boiler-superheater. In the boiler-superheater, heat is supplied by the water coolant to the first wall as well as by the hot helium. The relative duties provided by these two streams as well as the temperature driving forces in the boiler-superheater have been determined. The high-pressure superheater steam passes directly to the high-pressure turbine where some 524 MW of electric power is produced. The discharge steam is reheated in a ceramic regenerator after which it flows to the high-temperature steam modules in the blanket where it picks up about 1017 MW of thermal energy. It leaves at 1142°C at which temperature it enters the HTE units. The effluent from the HTE units pass through the ceramic regenerator and flow onto the low pressure turbine.

From the point of view of the power cycle, the high-temperature electrolyzers and their associated equipment has merely served to supply reheat to the steam leaving the high-pressure turbine. The total power output from the low-pressure turbine is somewhat over three times the output of the high-pressure turbine or about 1629 MW. The feed preheat exchangers which take extraction steam from the low-pressure turbine must be designed in such a way as to permit recovery of the hydrogen contained in the extraction stream. Furthermore, they must be designed with careful attention to countercurrent flow, at least so far as the hydrogen component is concerned, in order to reduce the moisture content of the hydrogen to as low a level as is practical.

The flow sheet shown in Fig. 3.1-1 has the oxygen product from the electrolyzers passing through the hot regenerator to the oxygen turbine and finally to a fuel preheat exchanger. If this waste oxygen is passed through the boiler-superheater instead of the hot regenerator, overall cycle efficiency increases somewhat since it results in a slightly reduced helium flow and a reduced amount of electricity consumed by the primary and secondary helium blowers.

C. Process Flow Sheet Summary

The process flow sheet which is shown in Fig. 3.1-1 contains four major process systems which are operating simultaneously in a highly coupled mode, namely:

1. DT fusion reactor;
2. steam/electric power system;
3. high-temperature electrolysis of water; and
4. hydrogen drying.

The DT fusion reactor has three functionally different coolant streams namely:

1. relatively cool water cooling the first wall of all modules;
2. hot helium cooling the interior of some modules; and
3. superheated steam cooling the interior of the remaining modules.

Streams 1 and 2 provide a thermal coupling to the steam electric power cycle since they jointly provide the energy to raise the steam. Thus, Streams 1 and 2 serve to determine how much steam will circulate through the power turbines and therefore have a direct influence on how much electrical power will be produced. Stream 3 provides a thermal coupling to the electrolysis process which is endothermic. Stream 3, therefore, has a direct influence on how much hydrogen product is made.

The steam-electric power cycle generates the electricity required to run all pumps, blowers, compressors, fusion reactor needs, and finally, the electric power needs of the HTE. It is through these electrical requirements (and the constraint that the overall process have a zero net electric generation) that this system is coupled to Systems 1, 3, and 4 above.

The hydrogen drying process consists of a series of compressors and cooler-condensers each of which removes a small portion of the residual undercomposed steam, while rejecting heat only to the atmosphere, i.e., no refrigeration is required. A total of eight stages of compression has been proposed with the same pressure ratio in each storage. Since the first few stages have a much larger flow than do the last few stages, it may be that a more judicious distribution of pressure ratio throughout the eight stages may result in an overall reduction of electric power requirements. It is also possible that replacing some of the initial compression stages with an absorption-desorption scheme for removing the water, with the heat of desorption coming in part from the heat of compression may also result in a significant reduction in electrical energy requirements. Table 3.1 is a summary of the HYFIRE plant parameters.

TABLE 3.1

SUMMARY OF HYFIRE PLANT PARAMETERS

Gross Blanket Thermal Power, MW(th)	6000	Blanket
Steam Exit Temperature, °C	1142	Blanket
Helium Exit Temperature, °C	732	
Pressure Turbine Inlet Temperature, °C	538	High
Pressure Turbine Inlet Pressure, MPa	8.50	High
Pressure Turbine Inlet Temperature, °C	474	Low
Pressure Turbine Inlet Pressure, MPa	3.38	Low
Electrical Power to Electrolyzers, MW(e)	1620	
Thermal Power to Electrolyzers, MW(th)	650	
Production: metric ton/day	1580	
kg/hr	65830	
Fusion Power to Hydrogen Conversion Efficiency, %	50	

4.0 FUSION/HTE PLANT INTEGRATION

4.1 Introduction

The objective of the design of the plant facilities for the two HYFIRE designs (Tokamak and Tandem Mirror) was to make them as similar to exisitng generic Tokamak and/or Mirror Fusion plants as feasible. Utilizing the study constraint, to the extent possible, that the HYFIRE reactor design was to be based on the STARFIRE Tokamak Commercial Power Reactor (Ref. 1), the STARFIRE site plant and building layouts, shown in Figs. 4.1-1 and 4.1-2, were used as the starting point for the HYFIRE Tokamak design. The general arrangement of the building and component transport system used for remote assembly and disassembly have been retained. The only changes that have been made for HYFIRE Tokamak are those required for the production of the hydrogen synthetic fuel and oxygen, and by the change in the thermal power level. The degree of detail shown in the STARFIRE design could not be provided by the lower budget for the HYFIRE project. The general description which follows will be for the HYFIRE Tokamak and utilizes some of the information previously reported in Ref. 2 modified as necessary to apply the latest design criteria.

The Fusion/HTE plant integration conceptual design has been carried out in accordance with the process flow diagram and process flow conditions given in Section 3, Process/Power Cycle. This Section of the report will discuss the building's physical condition, sizes of some of the components, and special considerations which influence the plant layout. This work was used to establish building sizes and locations. The development of the costing information will be covered in Section 5, Costing Analysis.

The site plan and the building locations are described. The basis for the sizing of the components is then described on a building-by-building basis.

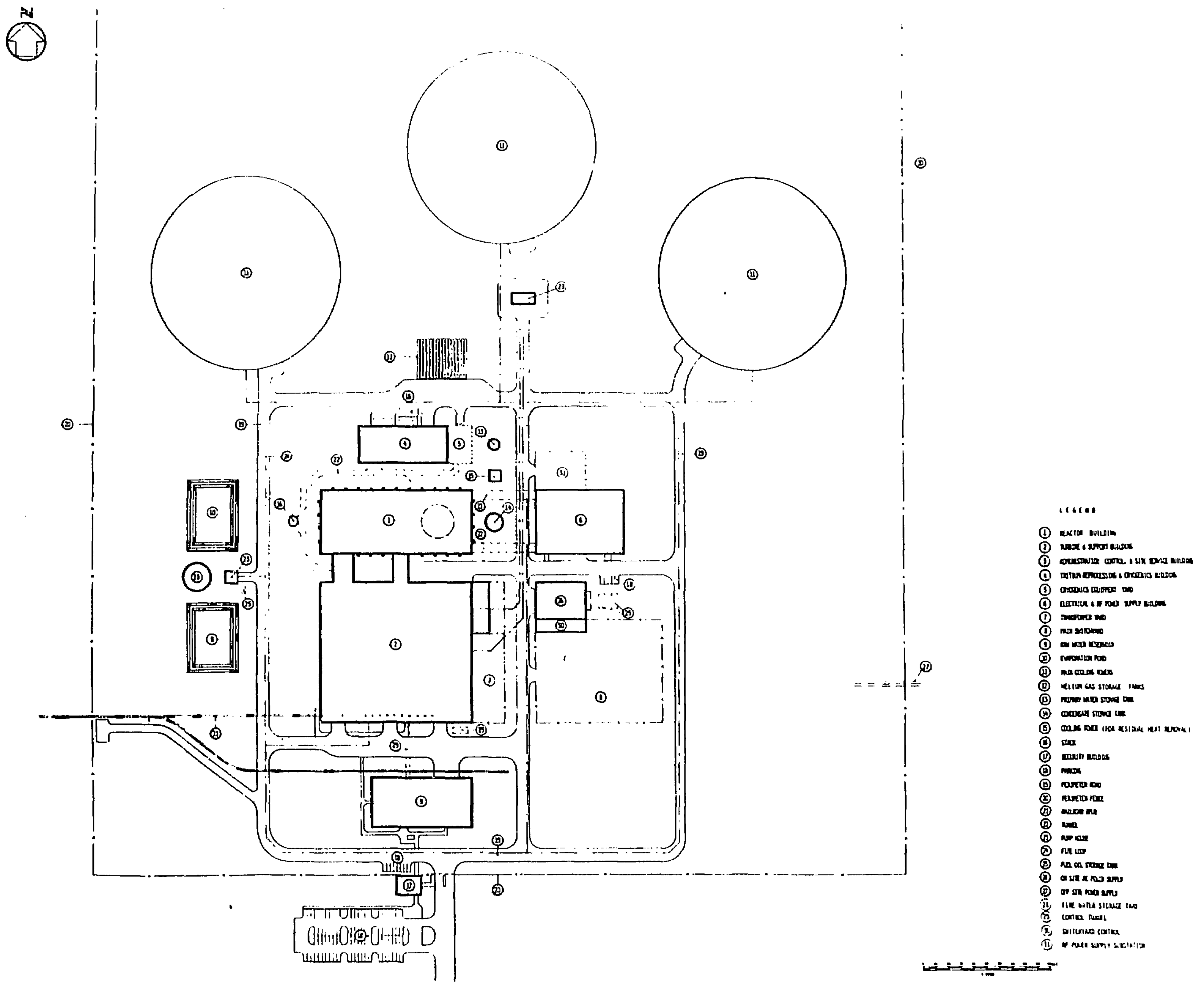


FIGURE 4.1-1 STARFIRE SITE PLAN

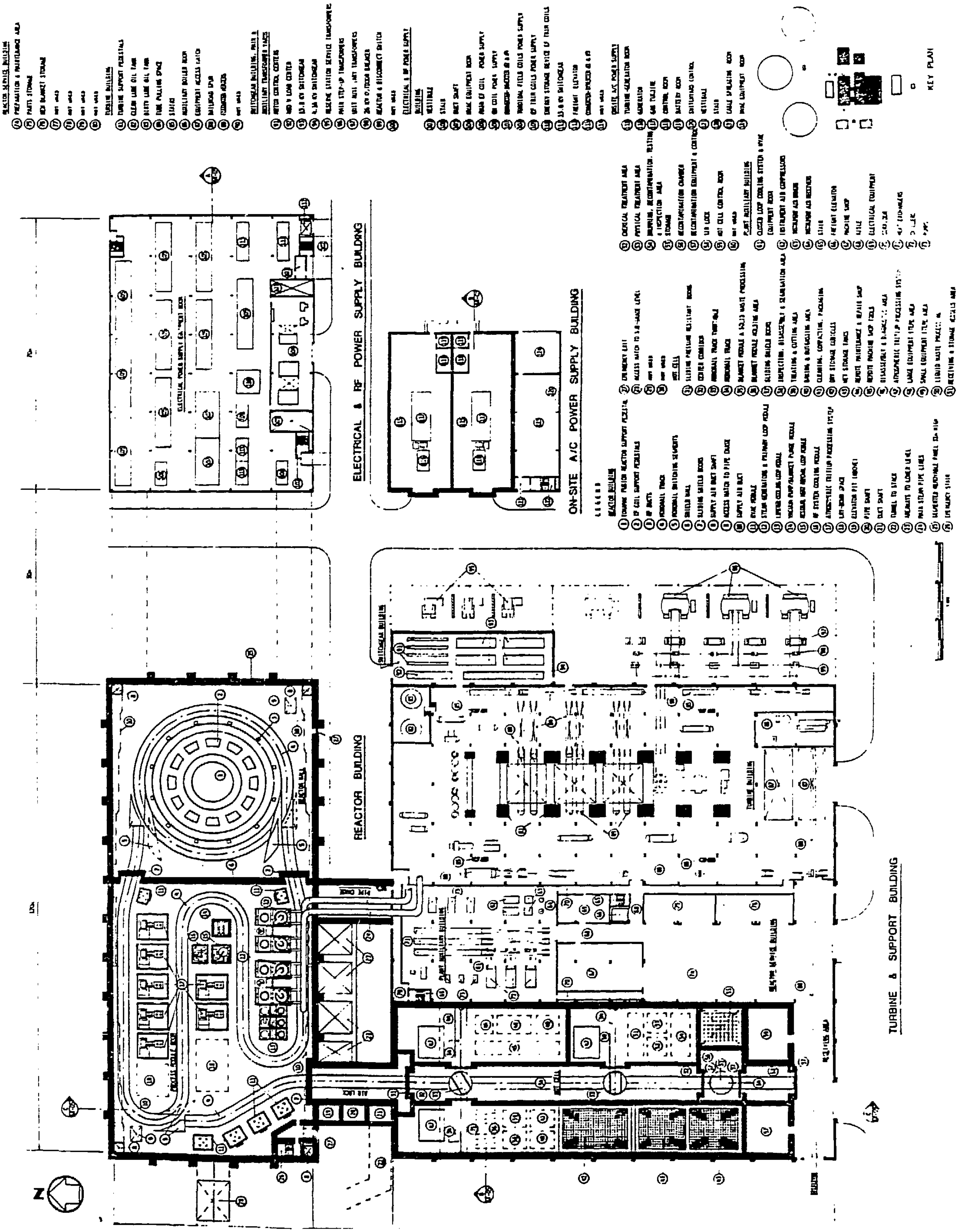

REACTOR BUILDING
TURBINE & SUPPORT BUILDING
ELECTRICAL & RF POWER SUPPLY BUILDING
ON-SITE A/C POWER SUPPLY BUILDING
KEY PLAN

FIGURE 4.1-2

4.2 HYFIRE Tokamak Site Plan

The HYFIRE Tokamak Fusion HTE reference design requires that the STARFIRE site plan of Fig. 4.1-1 be modified. The reactor building, Fig. 4.2-1, has been been increased in size from the STARFIRE dimensions of 50 x 120 m to ~55 x 130 m to accommodate the increase in the reactor major radius from 7 to 8.5 m. The process module room, at nearly the same size, is able to house the additional components. The new electrolyzer building which houses both the electrolyzers and recuperators has been added on two sides of the reactor building to minimize the length of the piping runs. The hot cell has been increased in size to accommodate the larger coils and blankets. The turbine building is much larger because the HYFIRE turbine operating conditions require that the steam plus one oxygen turbine be used, whereas STARFIRE had only one turbine. The high-pressure turbine and the oxygen turbine are new components which will be located in this building. The tritium processing building has been increased in size to handle the additional tritium produced by HYFIRE. The hydrogen and water separation building which houses the hydrogen processing and the hydrogen cleanup is separated from the other buildings for safety reasons. The electrical and rf power supply building is much larger than required by STARFIRE, not only because of the increased rf power required by the larger reactor but also because this building will house the rectifiers necessary to convert the ac power generated into the dc power required by the electrolyzers. One additional change, which is not shown in Fig. 4.2-1, is the increase in the size and number of water cooling towers to handle the additional water cooling requirements. (There are three 80°F cooling systems and one 90°F system.)

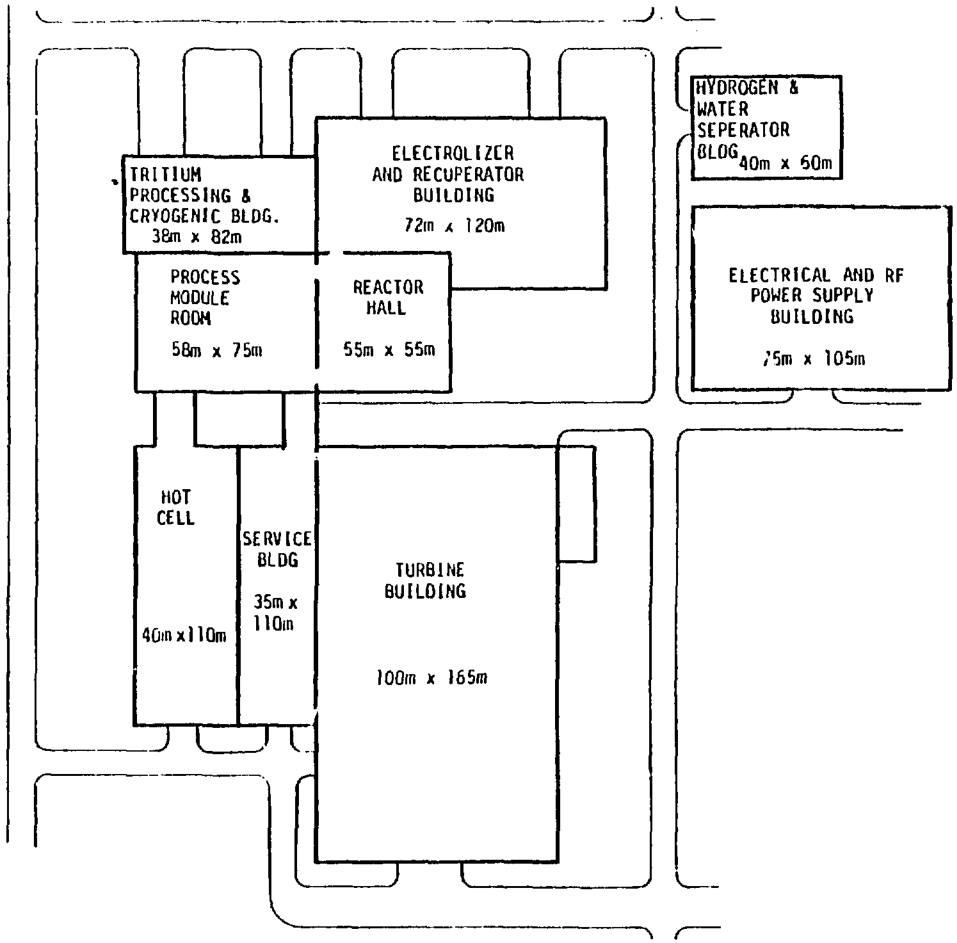


FIGURE 4.2-1 **Hyfire Tokamak Site Plan**

4.3 HYFIRE Tokamak Reactor Building

The layout of the reactor building, shown in Fig 4.3-1, has followed the STARFIRE design as far as possible in order that the single monorail system and the remote maintenance procedures developed for STARFIRE can be used without any major modification. Figure 4.3-1 does not present a complete detailed design for the reactor building, but does locate the major components. The drawings have been periodically upgraded, but due to the ongoing nature of the study, there may be minor inconsistencies between the drawings and the written text concerning the number and size of specific components. The text contains the latest available information.

An important feature illustrated in the figure is the location of the pumps for the primary helium loops. Figure 4.3-2 is a vertical cross section through a blanket sector between the TF coils which shows that the pumps are located at the sub-grade level below the reactor. This location provides the shortest piping runs between the pump and the helium-to-helium heat exchanger. Since this flow loop does not contain any component which is located away from the reactor, there is no reason to locate the pumps remotely and the location shown is therefore feasible. The STARFIRE design shows that this space is now occupied by the rf system, but it appears to be feasible for this system to be located in a sub-basement below the pumps. The rf system does not become contaminated and does not require remote control removal for maintenance. The primary helium pumps do become contaminated and should be capable of removal by remote handling. This will be accomplished in HYFIRE by making the ceiling sector directly over each pump, including a section of the monorail, as a removable cover. The pump would then be lifted from the basement by the overhead crane.

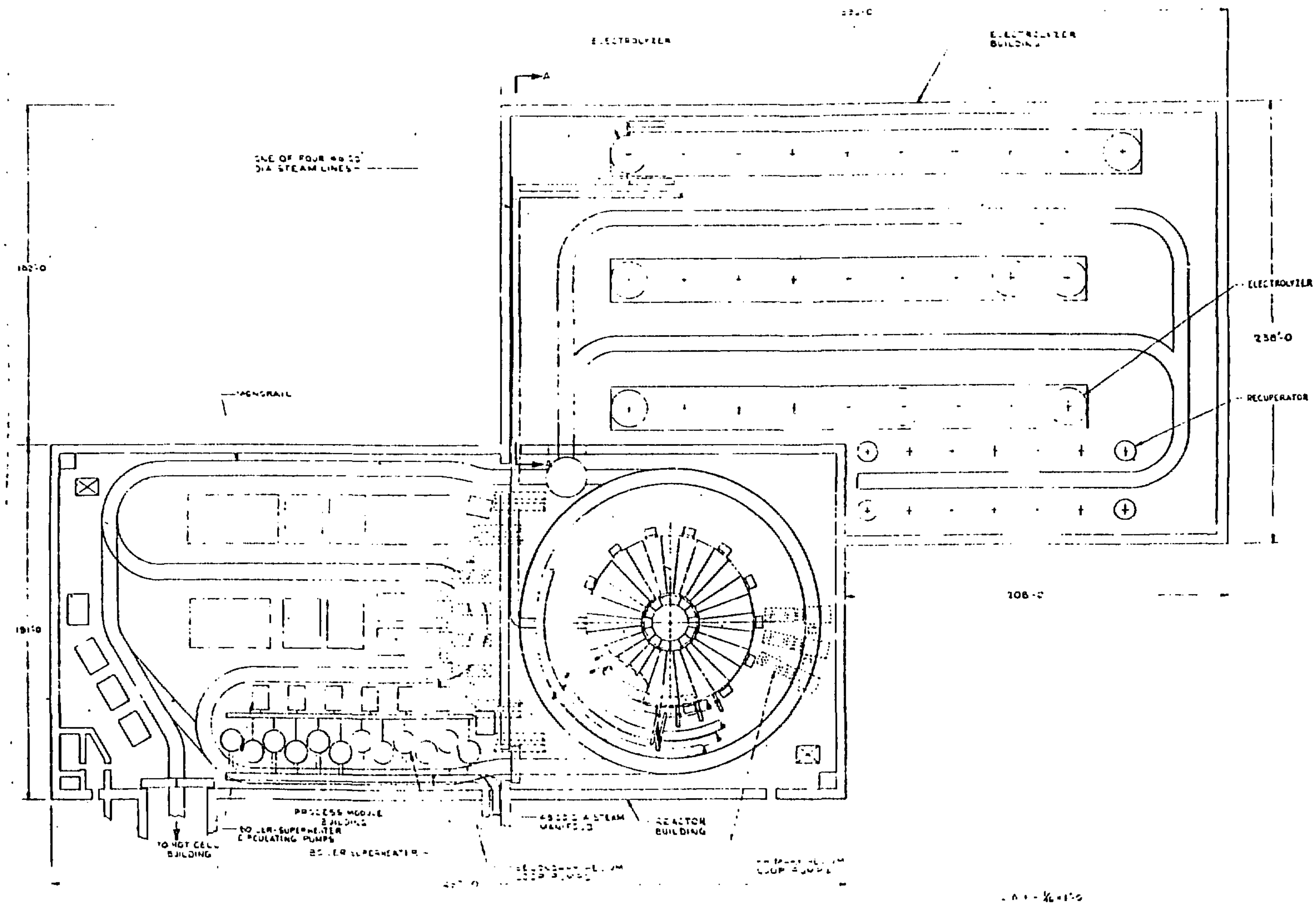


FIGURE 4.3-1 **Hyfire Tokamak Reactor Building Plan**

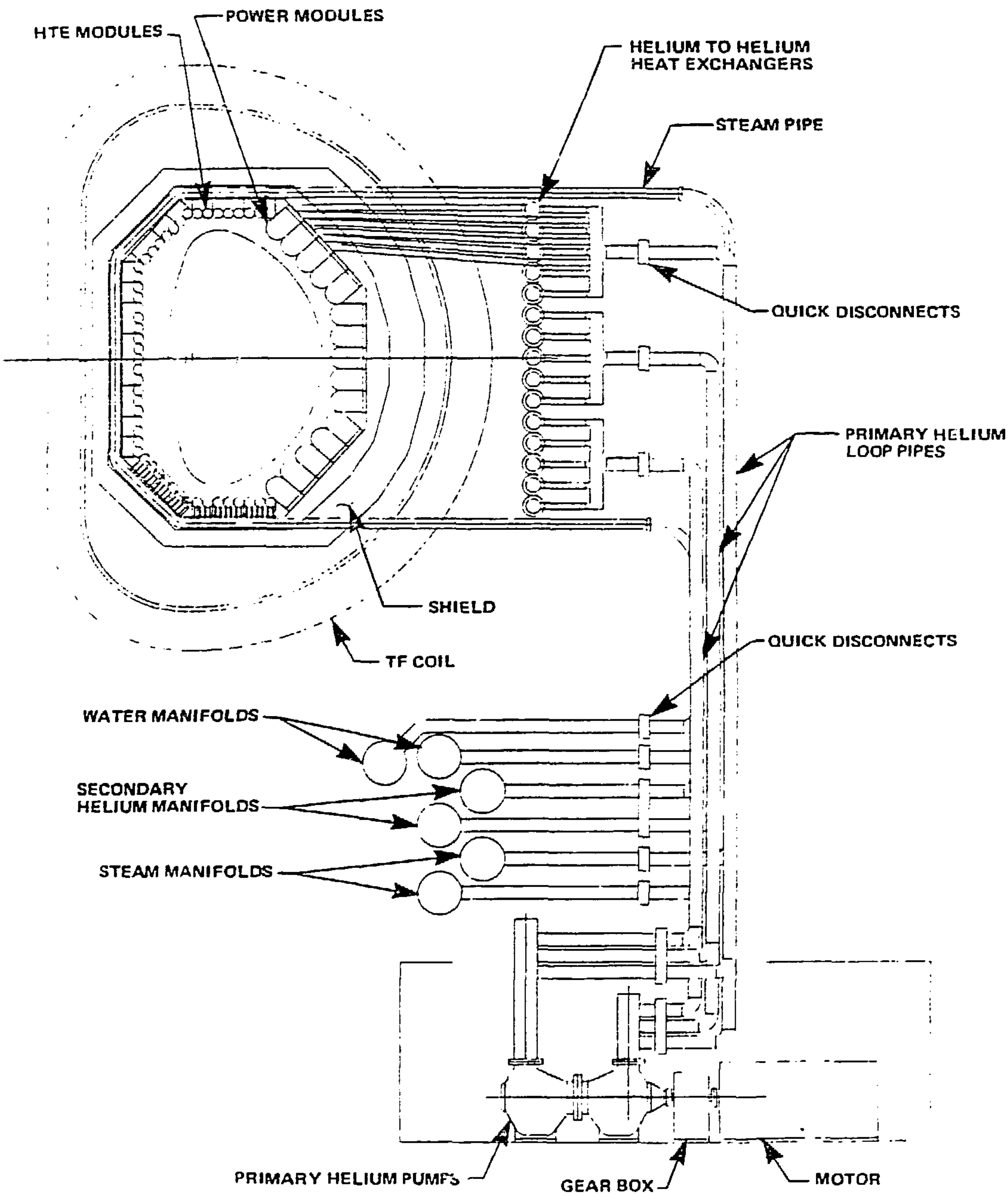


FIGURE 4.3-2 Hyfire Tokamak Vertical Section Through Blanket Sector

Also shown in Figs. 4.3-1 and 4.3-2 are the manifolds for the secondary helium loop and the high-temperature steam to the electrolyzers. This location and the design of the piping from the blanket sectors to the manifolds preserves the STARFIRE monorail concept for removal of a blanket sector from the reactor.

The general layout of the blanket is as much like the STARFIRE commercial reactor design as possible. The blanket is divided into twenty-eight sectors with one sector located under the TF coil and the adjacent sector between TF coils. The blanket sectors are removed horizontally by remote control utilizing a transport vehicle operating on a hydraulic pad monorail. The vacuum boundary for the plasma is located at the outside of the shield. The edges of the shield door are seal-welded to the opening in the vacuum vessel. All of the coolant lines which penetrate the shield door are permanently welded into the door. The helium-to-helium heat exchangers are part of the blanket and shield door assembly and are moved remotely with the assembly. A single high-temperature helium pipe and a single low-temperature helium pipe run between each of the fifteen modules and the fifteen heat exchangers. Groups of five pipes from the heat exchangers are manifolded together so that only six primary loop pipes need to be disconnected to permit the removal of the blanket, shield, and heat exchanger assembly. A single vertical pipe into and out of the heat exchanger is adequate for the secondary helium loop because it operates at a higher pressure.

Each of the twenty-eight blanket sectors has its own primary helium loop with its own pump. The activated pumps and piping are located inside the reactor containment. This arrangement also gives the shortest length of pipe and therefore the lowest pumping power for the primary loop. All of the blanket modules inside a blanket sector are connected in parallel to give a low-pressure drop. The primary loop flow passes through the shell side of the heat exchanger because it operates at a pressure of only 40 atm while the secondary helium flow at 70 atm is on the tube side of the heat exchanger.

The circular manifolds for the secondary helium loop, the HTE steam, and the blanket module cooling water are located below the reactor grade just as they are in STARFIRE. As in STARFIRE, the cluster of pipes which bring the coolants from the manifolds to a blanket sector are removable as a unit. When the pipes have been taken out of the way, the assembly made up of the blanket shield door and the heat exchangers is moved outward as a unit onto the transporter located on the monorail for transport to the hot cell building.

4.4 HYFIRE Tokamak Process Module Room of the Reactor Building

The process module room of the reactor building, selected for the location of the steam generators in the STARFIRE design is a good location for the boiler-superheaters of HYFIRE Tokamak. Figure 4.3-1 shows that they are close to the turbine building where the high-pressure turbine and the feed-water heaters are located and, at the same time, are close to the reactor so that the secondary helium piping will be short. This location is also on the opposite side of the reactor from the electrolyzer-recuperator building, so that there will be a minimum of interference between the large diameter piping of the HTE steam system and the large diameter piping of the secondary helium loop in the power generating system.

Also shown in Figs. 4.3-1 and 4.3-2 at the sub-grade level are the pumps for the circulation of the secondary loop helium to the boiler-superheaters. This space is not presently occupied by any major component in the STARFIRE design. These pumps are for helium which do not contain tritium and, therefore, do not need to be accessible to remote maintenance equipment. They will be moved on air pallets at the subgrade level to a point outside the reactor building if replacement is necessary.

Since components housed in the process module building are potentially activated or contaminated, the following items are included as was done in STARFIRE: a) atmospheric tritium process system, b) heating, ventilating and air-conditioning modules, c) limiter cooling loop module and lay-down work areas.

4.5 HYFIRE Tokamak Electrolyzer Building

The electrolyzer building is located adjacent to the reactor building and contains the electrolyzers and the recuperators (Fig. 4.3-1). The shape of this building was changed from the circular design, used in the FY 1981 HYFIRE study, Ref. 2, to a rectangular shape. This change was made to simplify the construction and reduce costs. The water-cooled, ceramic insulation-lined, high-temperature steam pipes cannot be bent but must be manufactured in their final shape. The circular design would have required the manufacture of curved pipes of three different radii. In addition, an overhead crane to follow the circular track would have been expensive. The layout of physical piping in accordance with the schematic diagram of the FY 1981 report, Fig. 4.5-1, showed that very little reduction in pipe length would be obtained by a circular arrangement. Shorter pipe runs were the primary reason for proposing this arrangement in the first place.

The cross section through the electrolyzer building, in Fig. 4.5-2, shows that the electrolyzers have been spaced further apart to permit the monorails to be positioned between them. The electrolyzers will become activated and therefore will have to be transported by remote control to the hot cell for disassembly and repair. Figure 4.5-2 shows that the pipe connections to the electrolyzers are made with quick disconnects so that a single vertical lift with the

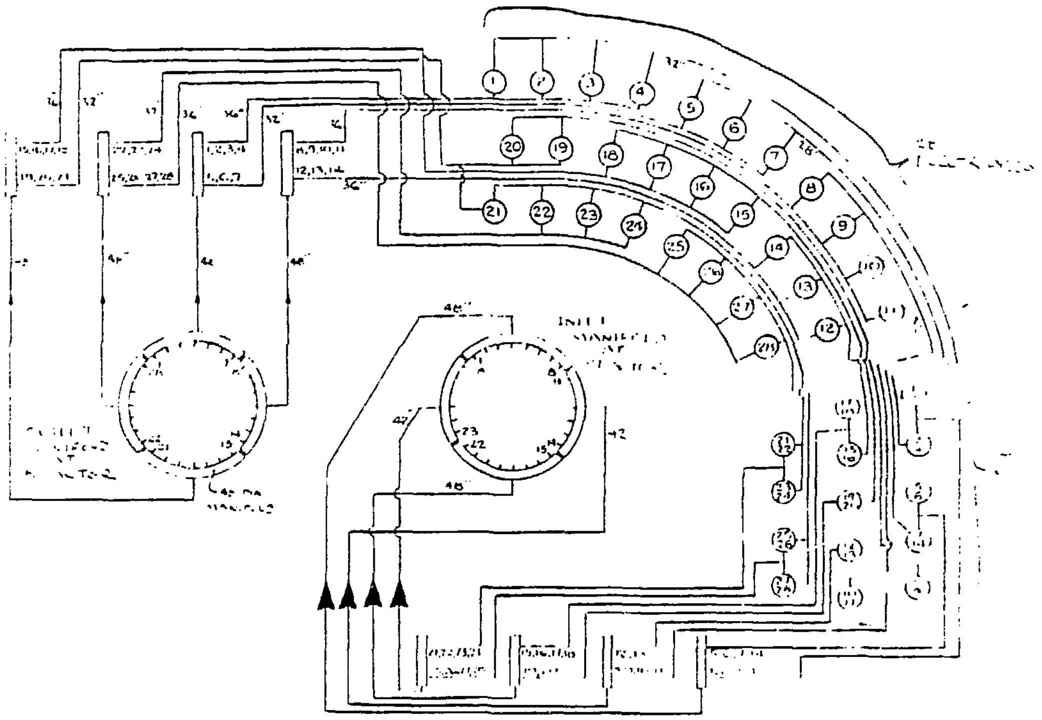


FIGURE 4.5-1 **Hyfire Tokamak HTE Steam Piping Schematic Diagram**

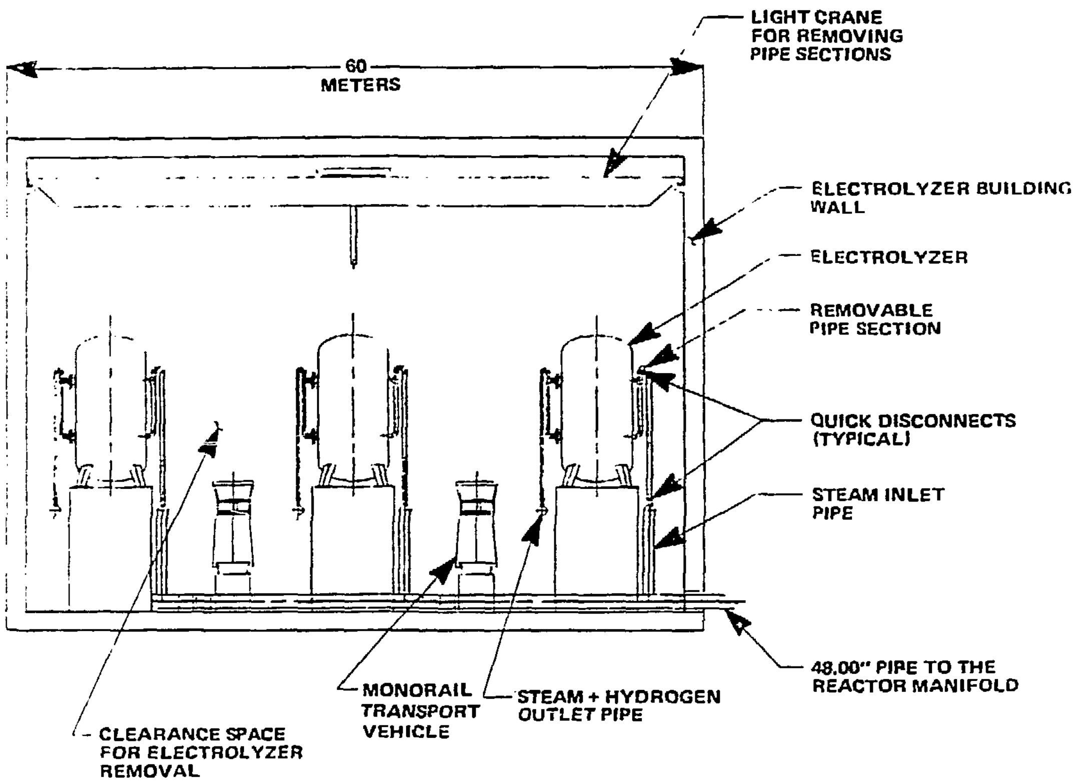


FIGURE 4.5-2 **End View of the Hyfire Tokamak Electrolyzer Building**

overhead crane will separate the pipes from the electrolyzer, and provide an unobstructed path for moving the electrolyzer horizontally across a short length of monorail bridge onto the monorail transporter. The overhead cranes can be light duty since they do not need to lift heavy electrolyzers. Extensions of the monorail past the electrolyzers permit the transporter to be used to remove the recuperators which will also become activated and require remote handling.

The heart of the fusion-driven hydrogen production plant is the bank of high-temperature, high-pressure steam electrolyzers. These units, which are based on reversed operation of the Westinghouse developed hydrogen-oxygen fuel cells for direct generation of electricity, take their supply of high-pressure-superheated steam from the fusion reactor array of steam modules. The ensuing vapor phase electrolysis generates two products, a heavily steam-laden hydrogen stream and a dry oxygen stream. These two product streams transfer part of their thermal energy via heat recuperators, to the steam exhausted from the high-pressure turbine which, in turn, is recycled back into the fusion reactor steam modules. The partially cooled product streams become inputs to two of the three turbires; the oxygen stream for the oxygen turbine and the heavily steam-laden hydrogen stream for the low-pressure turbine.

4.6 HYFIRE Tokamak Turbine Building

The turbine building, 100 x 165 m, houses the majority of the turbine plant equipment. This equipment takes the thermal energy from the two reactor heat transport streams (pressurized water and helium) and from the hydrogen-steam and oxygen product streams of the high-temperature electrolyzers, partially converts this thermal energy into electrical energy, and rejects the remaining energy to the heat rejection system. The conversion to electrical power is accomplished in three turbine-generators: a high-pressure turbine which operates on superheated steam; a low-pressure turbine whose feed is a steam/hydrogen mixture with a 0.09 mole H_2/mole H_2O ratio for the HYFIRE Tokamak; and an oxygen turbine. This is in contrast to the usual designs for fusion reactor-driven electric power plants, which normally operate only on steam. The equipment involved in the turbine plant serves the additional role of dewatering the entire hydrogen output of the high-temperature electrolyzers.

The turbine building houses the three plant turbine-generators. Each of the turbine generating units is a single 1800 rpm tandem-compound unit coupled to a hydrogen-inner-cooled synchronous generator. When operating with a 0.90 power factor, the turbine generator set overall thermal efficiency will be about 26%. The principal design/operational characteristics for the three turbines are shown in Table 4.6-1, and a list of some of the components housed in the turbine building is found in Table 4.6-2.

The extraction streams of the high- and low-pressure turbines and the exhaust from the oxygen turbine provide heating for the boiler-superheater feed water. Only the low-pressure turbine is coupled to a condenser. The low-pressure turbine is somewhat non-conventional in that the driving steam is heavily laden with the gaseous hydrogen product. The oxygen turbine is actually a conventional gas turbine.

A. Heat Rejection System

This system rejects the heat from the low-pressure turbine main condenser, the plant closed loop cooling water system, the hydrogen product post-compressor after-coolers, the feed-water preheater auxiliary heat exchangers, the cryogenic systems, the instrumentation and control system, the electrical

TABLE 4.6-1

HYFIRE TOKAMAK TURBINE PRINCIPLE DESIGN-OPERATION CHARACTERISTICS

	High-Pressure Turbine	Low-Pressure Turbine	Oxygen Turbine
Item	Tokamak	Tokamak	Tokamak
Feed Composition	100% H_2O	H_2O-0.09 mole H_2	100% O_2
Feed MW Thermal	1424	4424	155
Feed Temperature, °F	1000	866	1000
Feed Pressure, psia	1250	497	497
Extraction Stages	1	2	---
Exhaust Temperature, °F	759	138	271
Exhaust Pressure, psia	500	2.8	17
MW Electrical Output	524	1628	57
Feed Stream Source	Boiler-Superheater	H_2-H_2O Recuperator	O_2 Recuperator

TABLE 4.6-2

LIST OF TURBINE BUILDING COMPONENTS

Component
Low-Pressure Turbine
High-Pressure Turbine
Oxygen Turbine
Main Condenser
Feed-water Heater
Feed-water Auxiliary Condenser
Degassing Heater
Degassing Auxiliary Condenser
Feed Preheater
Booster Pump to Oxygen Cooler
Booster Pump to Feed Preheater
Booster Pump to Boiler-Superheater
Booster Pump to Feed-water Heater
Hydrogen Separation
Stage 1 Compressor
Stage 1 Intercooler
Stage 2 Compressor
Stage 2 Intercooler
Stage 3 Compressor
Stage 3 Intercooler
Stage 4 Compressor
Stage 4 Intercooler

components cooling loads, and other smaller equipment. Estimates of the total heat pump load was generated by calculating the heat rejection requirements for the largest contributors (main condenser, hydrogen product post-compression after-coolers, auxiliary heat exchangers) and augmenting this by an additional 30% to account for the load from the other contributors.

The heat is dumped to the atmosphere through four set-evaporative, natural-draft, hyperbolic cooling towers. Three of the towers yield 80°F cooling water, while the fourth generates 90°F cooling water. The bulk of the 80°F water is needed for the hydrogen product post-compression after-coolers.

B. Condensing System

The inlet stream to the main condenser is a portion of the hydrogen steam product of the high-temperature electrolyzer carrying a thermal heat load to the low-pressure turbine exhaust stream. Two streams issue from the condenser at an average back pressure of 2.8 psia; steam condensate and saturated hydrogen-steam vapor. Additionally, the condenser is fitted with a vapor after-cooler which cools the hydrogen-steam vapor to 95°F enroute to the raw hydrogen product conditioning system. The main condenser consists of a parallel operated array of heat exchangers, each exposing an active tube surface.

The presence of substantial amounts of hydrogen in the condenser feed leads to low overall heat transfer coefficients for the condenser and after-cooler and a large cost penalty for these units.

C. Feed-Water Heating System

This system includes all the components related to the feed-water heating. The system provides heated feed water to the steam generators, i.e., the boiler-superheater at controlled temperature, pressure, and flow rate as required to attain optimum efficiency of the high-pressure turbine. Four sources supply this heat: an extraction stream from the high pressure turbine; two extraction streams from the high pressure turbine; two extraction streams from the low-pressure turbine; and finally the exhaust from the oxygen turbine. The equipment array that comprises the feed-water heating system includes parallel-operated sets of feed preheaters, degassing heat exchangers, feed-water heaters, and booster pumps. The feed heater and degassing heat exchangers also serve to separate the hydrogen from the two extraction stages of the low-pressure turbines to produce saturated hydrogen-steam vapor. These streams are dispatched to the raw hydrogen product conditioning system at the appropriate stage in terms of the hydrogen-to-moisture ratio.

As in the case of the condensing system, the presence of hydrogen in two of the four heating streams engenders low overall heat transfer coefficients leading to the required large heat transfer surfaces and concomitantly high equipment costs.

In addition to the turbine plant piping, valves, supports, and hangers, this system also covers a number of small subsystems and equipment including blowdown and turbine plant cooling water.

4.7 HYFIRE Tokamak Hot Cell

The hot cell building shown in Fig. 4.2-1 has been increased in size over the STARFIRE dimensions in order to accommodate the greater aisle width required by the larger HYFIRE blanket sectors. Quite possibly the building will need to be further expanded to handle the larger steam generators, the electrolyzers, and the recuperators which do not exist in the STARFIRE plant. The need for additional hot cell facilities can be the subject for further studies.

4.8 Hydrogen and Water Separation Building

The hydrogen and water separation building is unique to a hydrogen producing plant. This building requires 40 x 60 m of floor space to house the many components associated with hydrogen production. Table 4.8-1 lists some of the installed equipment. One of the major systems involved is the raw hydrogen product conditioning system.

A. Raw Hydrogen Product Conditioning System

This system includes the installed equipment required for partial dehydration of the hydrogen product which is accomplished by subjecting the raw product to eight successive stages of compression and inter-stage cooling. The equipment involved includes multistage axial compressors, heat exchangers, instrumentation, flow splitters and controllers, and piping with various manifolds, valves, and supports.

The feeds to this system are the hydrogen plus water vapor streams emanating from the feed-water heaters, degassing heaters, and main condensers. On the average, a compression ratio of 1.73 is used for each of the stages. After-cooling back to 95°F in each stage is effected by the 80°F plant cooling water system, with the cooling water flow rate adjusted to control the cooling water temperature at the point of condensation onset equal to or less than 90°F, or to a discharge temperature at the after-cooler exit less than 150°F. The compressions are taken to be polytropic rather than isentropic, with a polytropic factor of 1.36 applied against the specific heat ratio for the H_2-H_2O vapor mixtures, and a 95% efficiency is assumed for the compressor drive motors. A 0.5 psi pressure drop is specified across each of the inter-coolers. All of the condensates are recycled to the feed-water heating system. Four compressors

TABLE 4.8-1

LIST OF HYDROGEN AND WATER SEPARATION BUILDING COMPONENTS

Component	No. of Units HYFIRE Tokamak
Oxygen After-Cooler Cooling Water Circulating Pump	2
Water Feed to Preheater Circulating Pumps	5
Feed Preheaters	4
Desuperheater Condensers for Degassing Heater	4
H_2-H_2O Vapor After-Cooler	1
Desuperheater Condensers for Feed-Water Heater	7
H_2-H_2O Vapor After-cooler of Feed-Water Heater	8
Vapor Compressors for Hydrogen Conditioning System (8 stages)	25
Inter-Cooler Condensers for Hydrogen Conditioning System	8
Vapor Compressors for Raw Hydrogen Conditioning and Polishing (3 stages)	12
Inter-cooler Condensers for Raw Hydrogen Conditioning and Polishing	3

and one after-cooler are provided for each of the eight stages. The processing achieves a 0.99 hydrogen mole fraction, corresponding to an end product with a moisture content of 4.72 wt. %.

B. Hydrogen Product Conditioning and Polishing

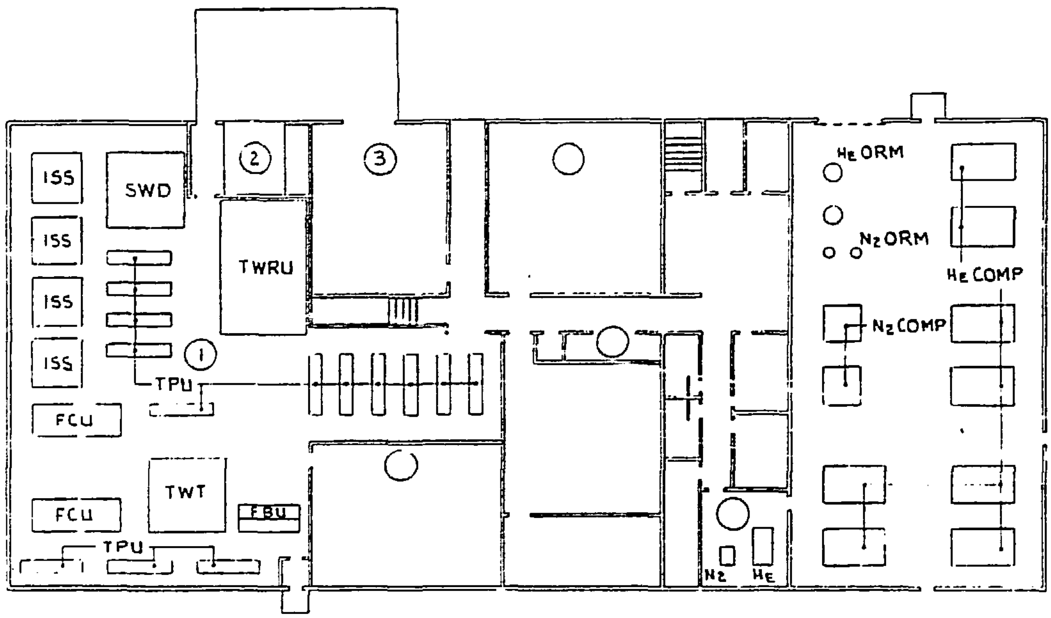
Another group of components required is the hydrogen product conditioning and polishing equipment. This includes the components associated with treating the end stream of the raw hydrogen product conditioning system to transform it into bone-dry decontaminated hydrogen which is the end product of the fusion driven synfuel plant. The processing operations involved to achieve these results include: 1) three additional stages of compression with after-cooling to 85°F; 2) high-pressure scrubbing in water to trap any residual radioactivity; 3) desiccating the hydrogen by means of molecular sieves; and 4) concentrating the radioactivity picked up by the scrub water by multiple effect evaporation, followed by dispatching the concentrate to the plant radwaste facility for ultimate disposal.

The principal equipment needed to achieve the described processing includes: twelve compressors; three after-coolers; one scrubbing tower; two scrub water circulating pumps; three molecular sieve desiccating columns; one triple effect evaporator operated in the forward flow mode; instrumentation and controls; and an array of piping with valves and supports.

4.9 HYFIRE Tokamak Tritium Reprocessing and Cryogenic Building

The HYFIRE Tokamak tritium reprocessing and cryogenic building is the same as was reported in Ref. 2 and is shown here for facility completeness.

Figures 4.9-1 and 4.9-2 show the ground level and upper level plans and Fig. 4.9-3 shows the elevation, respectively, for this building. The components



GROUND LEVEL PLAN

FIGURE 4.9-1 **Ground Level Plan Tritium Reprocessing and Cryogenic Building**

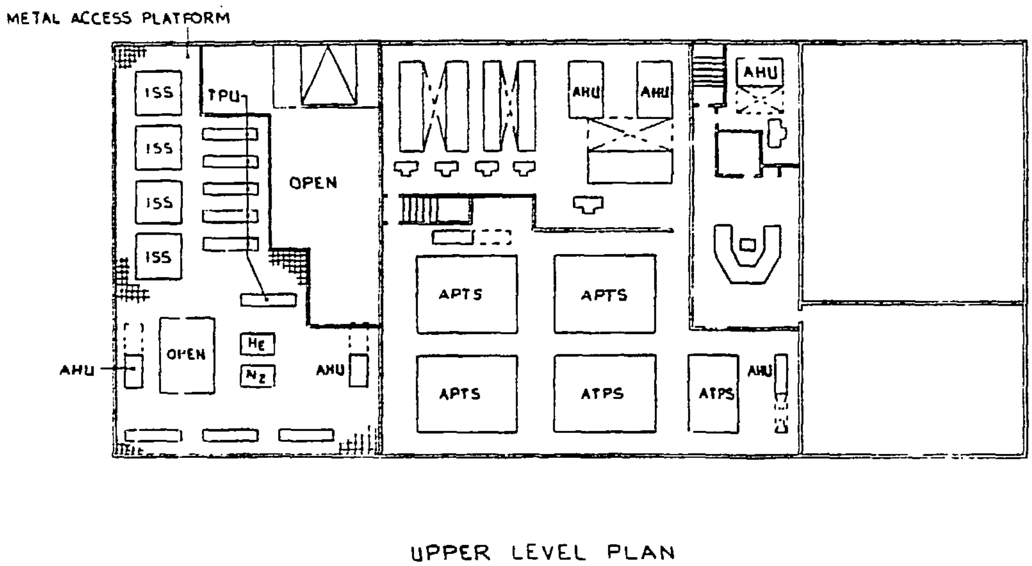


FIGURE 4.9-2 **Upper Level Plan Tritium Reprocessing and Cryogenic Building**

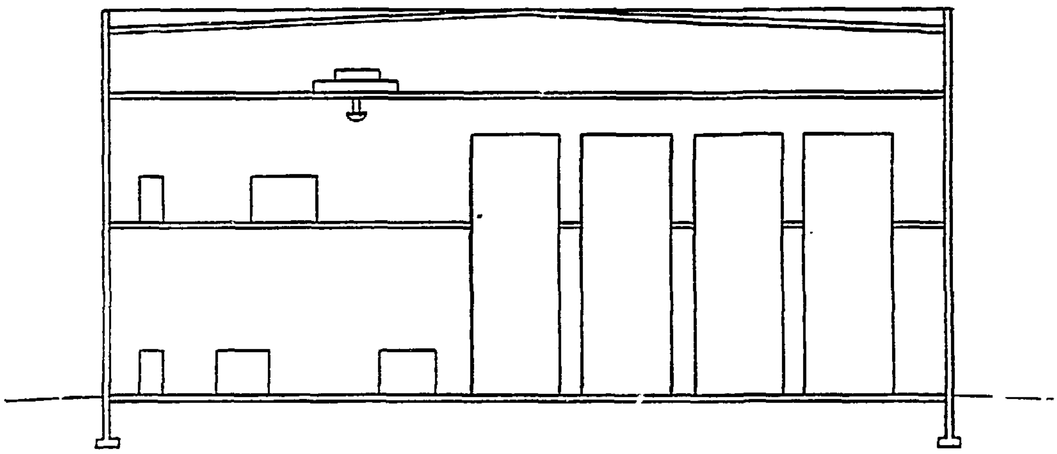


FIGURE 4.9-3 **Elevation Cross Section of the Tritium Reprocessing and Cryogenic Building**

are arranged in the building essentially as shown in the STARFIRE report (Ref. 1) Figure 20-11. The HYFIRE Tokamak components will require more space because of the larger amount of tritium handled and stored. STARFIRE is a 4000 MW(th) unit while HYFIRE Tokamak is 6000 MW(th), and the tritium burnup in STARFIRE is 42% while it is only 35% in HYFIRE Tokamak. Accordingly, the ratio of tritium fuel/day used by the HYFIRE Tokamak compared to STARFIRE is:

$$\frac{6000 \times 0.42}{4000 \times 0.35} = 1.8 \quad .$$

It is estimated that the space requirements for HYFIRE's tritium handling units would on the average have $(1.8)^{2/3} = 1.48$ larger cross section than those for STARFIRE, so a linear factor of $(1.8)^{1/3} = 1.22$ applies. This scaling does not apply for the tritium storage units which for HYFIRE Tokamak would be based on about 10+ days of capability compared with less than one for STARFIRE. Here a factor of approximately $[(6000 \times 0.42/4000 \times 0.35) \times (10)]^{0.333} = 2.6$ is applied on the height. The dimension requirements for individual components based on Table 14.3 of the STARFIRE report become those shown in Table 4.9-1. These are the dimensions used for the components in Fig. 4.9-1.

The HYFIRE building dimensions for the tritium processing area were scaled up also by approximately the 1.22 linear factor. The operations control and cryogenics area which should not change with the tritium volume handled was retained at a width of 40 m to give an overall building length of 80 m.

4.10 Electrical and rf Power Supply Building

In the HYFIRE Tokamak site plan of Fig. 4.2-1, the area has been doubled over that shown for STARFIRE in Fig. 4.1-1. The area required for the rf power supplies is increased in proportion to the increase in thermal output from 4000 to 6000 MW(th). An equal area is alloted to the rectifiers which provide direct current to the rectifiers, a component which was not required in STARFIRE.

TABLE 4.9-1

DIMENSIONS OF TRITIUM HANDLING COMPONENTS DERIVED FROM STARFIRE REPORT TABLE 14-3

Component	STARFIRE Dimensions m	STARFIRE Dimensions m^3	HYFIRE TOKAMAK Dimension m	HYFIRE TOKAMAK Dimension m^3
Atmospheric T Recovery	6.25x8x5	2500	7x9x5	3150
Units (ATR)	(1 unit)	(10 units)		(10 units)
Isotope Separation System	3x3x12	108	4x4x12	192
Fuel Cleanup Unit (FCU)	6x2x2	24	7x2.5x2	35
T Waste Treatment (TWT)	5x5x5	125	6x6x5	180
Solid Waste Disposal (SWD)	5x5x4	100	6x6x4	144
Transfer Pump Unit (TPU)	4x1x2	8	5x1x2	10
T Storage (TS)	8x4x2	64	8x4x5	160
Tritiated Water Recovery Unit (TWRU)	6x9x3	162	7x11x3	231
Fuel Blender Unit (FBU)	4x1x2	8	5x2x2	20

4.11 Heat Rejection System

The heat rejection system rejects the heat from the low-pressure turbine main condenser, the plant closed loop cooling water system, the hydrogen product post-compressor after-coolers, the feed-water preheater auxiliary heat exchangers, the cryogenic systems, the instrumentation and control system, the electrical components cooling loads, and other smaller equipment. Estimation of the total heat dump load was generated by calculating the heat rejection requirements for the largest contributors (main condenser, hydrogen product post-compression after-coolers, auxiliary heat exchangers) and augmenting this by an additional 30% to account for the loads from the other contributors.

The heat is dumped to the atmosphere through four wet-evaporative, natural-draft, hyperbolic cooling towers. Three of the towers yield 80°F cooling water, while the fourth generated 90°F cooling water. The bulk of the 80°F water is needed for the hydrogen product post-compression after-coolers.

Table 4.11-1 lists the main parameters and equipment for the heat rejection system.

TABLE 4.11-1

PRINCIPAL PARAMETERS FOR THE HEAT REJECTION SYSTEM

Item	HYFIRE Tokamak
80°F System Cooling Towers	
Mean Inlet Temperature, °F	123
Heat Dump, MW	4190
Design Flow Rate, gpm	768,000
90°F System (1 Cooling Tower)	
Mean Inlet Temperature, °F	102
Heat Dump, MW	303
Design Flow Rate, gpm	175,000

5. COSTING ANALYSIS

5.1 General

The cost of producing hydrogen using a fusion reactor as the basic heat source involves the utilization of various source materials. Since the STARFIRE Study (Ref. 1) performed a very detailed analysis of the overall cost for a power producing Tokamak fusion reactor, it was used as the starting basis for the determination of the majority of the costs associated with the reactor plant equipment, balance-of-plant equipment, land, and other related structures and site facilities. The basic information was modified as required to adapt it to a hydrogen producing plant with a 50% increase in thermal power. The items which were not modified were updated by applying an escalation factor to account for the changes from 1980 to 1981 costs.

The STARFIRE and HYFIRE studies used the DOE guidelines which were outlined in Refs. 2 and 3. All estimated costs in this report are September 1981 dollars unless stated otherwise.

It was necessary to make specific assumptions and to scale the cost data to account for the major change of the HYFIRE-Tokamak reactor generating 6000 MW(th) as opposed to STARFIRE generating 3500 MW(th). The two reactors are very simmilar with the main differences being in the overall size and the blanket configurations.

Many of the components in the HYFIRE plants are not found in STARFIRE because they are unique to the hydrogen production plant, e.g., the electrolyzers and the hydrogen conditioning components. The latter includes components such as vapor compressors, intercooler condensers, scrubbing towers, recuperators, etc. These components were sized as required by the process flow sheet and cost estimates made. As the study progressed, additional information became available which resulted in some components being re-estimated and/or moved to different account numbers. Since it was not feasible to revise all the original work, there may be slight numerical inconsistencies between this Section and Appendix C which have no effect on the final information appearing in Capital Cost Summary Tables 5.3-1 and 5.3-2. These cost models followed the basic considerations which were used in the development of the COAST code. Since these original calculations, made for individual components required for the hydrogen production, were limited to the bare pieces of equipment, it was necessary to provide the proper adders to arrive at the "installed component cost." The following are considered necessary ingredients to provide "as installed cost" data:

A. Installation, labor, foundations, supports, platforms, construction expenses, etc;

B. Piping, valves, fittings, supports;

C. Electrical: power, lighting, instrument wiring;

D. Engineering: design, supervision, testing and checkout, overhead, drafting, QA, purchasing, reproductions, etc.;

E. Shipping and transportation;

F. Administration;

G. Contractor and installer fee; and

H. Insulation.

In the absence of rather detailed equipment layouts, exact piping sizes, and limited time for in-depth evaluation, making estimates for the above adders is difficult. Some guidance for making these estimates is furnished by Peters and Timmerhaus.[4] The above adder items were individually evaluated for each component and cost estimated. These adder costs have been summarized in Table 5.1-1 for the HYFIRE Tokamak components.Since the plant is considered to be the "tenth-of-a-kind for a specific design technology," the adder percentages were not consistently used for each component. Judgment was utilized in order that undue adders would not be incorporated. As an example the "Engineering and Design" factor actually used ranged from less than 1.0 to 22% of the base component cost.

5.2 Hydrogen Producing Components for HYFIRE

There are a large number of components in the hydrogen production plant that had to be costed. This is evident from the flow sheet in Section 3. The costing of each component was based on a design of each component. The designs and sizing of the components were developed from the state points given in the flow sheet. The cost determinator differs depending on the specific type of component involved. The cost algorithms used are discussed in Appendix C. As an example, the cost determinator for evaporators, heat exchangers, and condensers is the square feet of heat transfer surface area and the design pressure. The cost determinators for compressors are brake horsepower and the design pressure, while for pumps it is gallons per minute.

The sizing of the components was based on common engineering practice and engineering experience. For example, heat exchangers were sized based on the amount of heat transferred, approximate heat transfer coefficients, and log mean temperature differences. Individual components associated with the synfuel plant are discussed in Appendix C and any special conditions are described therein. However, the details of the calculations are not given.

Since some of the components would be excessively large in a single unit, one or more units were specified based on the ratings of commercially available

TABLE 5.1-1

Summary Cost Adders for Hyfire Tokama

NO. OF UNITS	ITEM	BARE EQUIPMENT COST	INSTALLATION	PIPING	INSULATION
420	He-He HEAT EXCHANGER	121.79	24.358	60.895	–
28	PRIM. He CIRC. COMPRESSOR	41.26	8.250	20.630	–
28	SEC. He CIRC. COMPRESSOR	22.67	4.534	11.335	–
8	O_2 REGEN. COOLER	1.88	0.376	0.940	0.150
20	H_2 RECUPERATOR	166.40	3.328	83.200	13.312
1	O_2 RECUPERATOR	5.54	1.107	0.554	0.443
12	BOILER SUPERHEATERS	202.50	40.500	101.250	16.200
15	FIRST WALL H_2O CIRC. PUMP	4.55	0.871	2.177	0.348
2	O_2 AFTER-COOLER CIRC. PUMP	0.157	0.031	0.078	–
5	FEED PREHEAT. CIRC. PUMP	1.021	0.204	0.511	0.082
6	BOILER SUPERHEAT. CIRC. PUMP	1.42	0.285	0.713	0.114
5	MAKE-UP H_2O CIRC. PUMP	0.432	0.086	0.216	–
4	FEED PREHEATER	35.80	7.16	17.900	2.864
4	DEGASSING HEAT EXCHANGER	6.92	1.384	3.460	0.554
1	DEGAS. HEATER VAPOR AFT. COOLER	0.172	0.035	0.088	0.014
7	FEED WATER HEATER	34.577	4.915	12.289	1.966
2	FEED WATER HEATER VAPOR AFT. COOLER	2.758	0.552	1.379	–
16	MAIN CONDENSER	60.02	12.004	30.010	4.802
1	MAIN COND. VAPOR AFT. CL.	0.172	0.034	0.086	–
25	VAPOR COMPRESSOR (STAGES 1-8)	16.818	3.364	8.409	–
8	INTERCOOLER (STAGES 1-8)	25.888	5.178	12.944	–
12	PRODUCT COND. COMP (STAGES 9-11)	11.215	2.243	5.608	–
3	INTERCOOLERS (STAGES 9-11)	21.823	4.365	10.912	–
1	H_2 SCRUBBING TOWER, PUMPS AND PALL RINGS	3.122	0.624	1.479	–
1	SCRUB WATER EVAPORATOR	1.373	0.275	0.687	0.110
3	DRYING TOWERS, MOLECULAR SIEVE (RESIN) AND AUXILIARIES	10.304	2.066	4.228	–
4	PLANT COOLING WATER SYST.	68.13	13.626	34.065	–
28	HIGH TEMP. ELECTROLYZER	208.90	41.780	104.45	16.710

TABLE 5.1-1

Adders for Hyfire Tokamak Components ($M)

NG	INSULATION	SHIPPING	ELECTRICAL	ENGINEERING	ADMINISTRATION	CONTRACT FEE	TOTAL INSTALLED COST
95	–	2.535	–	0.128	0.023	7.307	217.04
30	–	0.825	2.888	0.234	0.059	2.476	76.71
35	–	0.453	1.587	0.178	0.032	1.360	42.15
40	0.150	0.038	–	0.052	0.009	0.113	3.56
00	13.312	3.521	–	1.830	0.333	9.984	311.67
54	0.443	0.055	–	0.277	0.221	0.332	3.56
50	16.200	4.050	–	3.712	0.675	12.150	381.04
77	0.348	0.087	0.305	0.128	0.012	0.261	8.54
78	–	0.003	0.011	0.017	0.003	0.009	0.31
11	0.082	0.020	0.071	0.045	0.008	0.061	2.02
13	0.114	0.029	0.100	0.063	0.011	0.086	2.83
16	–	0.003	0.030	0.019	0.003	0.026	0.82
00	2.864	0.716	–	1.969	0.358	2.148	68.92
60	0.554	0.138	–	0.381	0.069	0.415	13.22
88	0.014	0.004	–	0.039	0.007	0.011	0.37
89	1.966	0.492	–	0.077	0.140	1.480	46.13
79	–	0.055	–	0.303	0.055	0.165	5.27
10	4.802	1.200	–	0.825	0.150	3.60	112.61
86	–	0.003	–	0.038	0.007	0.010	0.53
09	–	0.336	1.177	0.462	0.084	1.009	31.66
44	–	0.518	–	5.695	1.036	1.553	52.81
08	–	0.224	0.785	0.822	0.150	0.673	21.72
12	–	0.436	–	4.801	0.873	1.309	44.52
79	–	0.062	0.003	0.646	0.118	0.187	6.71
37	0.110	0.027	0.096	0.302	0.055	0.082	3.01
28	–	0.207	0.578	0.648	0.118	0.620	18.80
55	–	1.636	4.769	4.996	0.908	4.088	68.17
5	16.710	4.18	14.62	2.099	0.840	12.530	406.09

equipment. Because there are cost savings in the manufacture and purchase of multiple units, discounts in the total cost of 5, 10, and 15% are taken for two, three, and four units, respectively.

The size of the components, number of units of each type, the scaling parameters, scale and cost coefficients, and the total cost (of one or more units) are summarized in Table 5.2-1.

Note that the hydrogen production components primarily affect Cost Account 22 (Reactor Plant Equipment) and Account 23 (Turbine Plant Equipment). The basic costing algorithm is given by the equation

$$\text{Cost/Unit} = \$C_o Y_o (A)^{\alpha_1} (P)^{\alpha_2} (B)^{\alpha_3} (W)^{\alpha_4} (M)^{\alpha_5} (Q)^{\alpha_6}$$

where C_o is the cost coefficient, Y_o, is a multiplicative factor, α_1, α_2, α_3, α_4, α_5, and α_6 are scale factors. The variables in parentheses are the scaling parameters. A is the external heat transfer surface area, P is the component design pressure, B is the brake horsepower, W is the flow rate in gpm, M is the mass of the unit, and Q is the power output. This equation is applicable to essentially all types of equipment, depending on the value of the scale factors specified. For example, for heat exchangers, α_3, α_4, α_5, and α_6 are zeros and Y_o = 1, thus the costing algorithm reduces to

$$\text{Cost/Unit} = \$C_o (A)^{\alpha_1} (P)^{\alpha_2}$$

5.3 Capital Cost Account

A. Cost Accounting Format

The DOE guideline for the cost accounting format provided in Ref. 2 was used for the HYFIRE study. STARFIRE[1] costs were developed from this

TABLE

SUMMARY OF COMPONENT DESIGN PARAMETERS, COST COEFFICI

Cost/Unit = $ $C_0 \gamma_0$ $(A)^{\alpha_1}$ $(P)^{\alpha_2}$

Account	Item	Number of Units	Overall Dimensions (Space Req'd) ft. O.D. x ft. long	A External Heat Transfer Surface ft^2	P Design Pressure psia	B Brake Horsepower, BHP
22.02.01	Primary to Secondary Helium Heat Exchangers	420	1.33 x 11.67	820	1030	
22.02.02	Primary Helium Circulating Compressors	28	8.3 x 9.9		720	9,000
22.02.03	Secondary Helium Circulating Compressors	28	6.1 x 7.4		1570	
22.02.04	Oxygen Regenerative Coolers	8	3.1 x 12.8	3,818	1150	
22.02.05	Boiler Superheaters	12	11.6 x 42.2	6.4×10^4	4350	
22.02.06	Pressurized Water Circulating Pumps	13	9.2 x 13.7		4380	510
23.01	Turbine Generators – O_2 Turbine – High Pressure Turbine – Low Pressure Turbine					
23.03.01	Plant Cooling Water Heat Dump System 80°F System 90°F System	 3 1				
23.03.02	Water Recirculating Pump	8				
23.04.01	Main Condensers	16	10.42 x 61.08	174,840	30	
23.04.02	H_2O-H_2 Vapor After-Cooler for Main Condensers	25	3.79 x 13.5	3,770	30	
23.05.01	Oxygen After Cooler, Cooling Water Pumps	3	3.6 x 5.3		1130	890
23.05.02	Circulating Pumps for Water Feed-to-Feed Preheater	3	9.2 x 13.2		1130	12,650
23.05.03	Circulating Pumps for Water Feed-to-Boiler Preheater	6	9.2 x 13.2		1900	12,650
23.05.04	Circulating Pumps for Make-Up and Recycle Water	5	9.2 x 13.2		60	12,650
23.05.05	Feed Preheaters	4	7.25 x 67.75	150,230	1130	
23.05.06	Desuperheater-Condenser for Degassing Unit	4	9.17 x 45.5	98,530	60	

*Component Hardware Costs Only

TABLE 5.2-1

T COEFFICIENTS, SCALE FACTORS AND COSTS FOR THE HYFIRE (TOKAMAK)

$(A)^{\alpha_1} (P)^{\alpha_2} (B)^{\alpha_3} (W)^{\alpha_4} (M)^{\alpha_5} (Q)^{\alpha_6}$

B Brake Horsepower, BHP	W Flowrate GPM	M Mass, lb	Q Turbine Output, MW	Co Cost Coefficient	α_1	α_2	α_3	α_4	α_5	α_6	γ_0	Total * Cost (one or more units) $ M
				498	0.646	0.293	0	0	0		1	121.8
9,000				1800	0	0	0.733	0	0		1	41.3
				245.8	0	0.293	0.723	0	0		1	22.7
				602.6	0.473	0.293	0	0	0		1	1.88
				1136	0.640	0.293	0	0	0		1	202.5
510	12,000			1100	0	0.293	0	0.337	0		1	4.55
			109.7 497 155.6	5.56×10^4 5.56×10^4 5.56×10^4	0 0 0	0 0 0	0 0 0	0 0 0	0 0 0	0.6 0.6 0.6	1 1 1	1.0 2.30 1.15
	2.17×10^5 2.73×10^5			755.8 493.5	0 0	0 0	0 0	0 0	0.82 0.82		1 1	53.8 14.2
				1098.0	0	0	0.337	0	0		1	0.12
				568.2	0.646	0.293	0	0	0		1	60.02
				310	0.646	0.293	0	0	0		1	0.17
890	700			1100	0	0.293	0	0.337	0		1	0.23
12,650	12,000			1100	0	0.293	0	0.337	0		1	1.02
12,650	12,000			1100	0	0.293	0	0.337	0		0.01	1.43
12,650	12,000			1100	0	0.293	0	0.337	0		1	0.43
				516.5	0.646	0.293	0	0	0		1	35.8
				310	0.646	0.293	0	0	0		1	6.92

TABLE 5.2-1 (CONTINUED)

SUMMARY OF COMPONENT DESIGN PARAMETERS, COST COEFFICIENTS, SCALE

Cost/Unit = $ $C_o \gamma_o (A)^{\alpha_1} (P)^{\alpha_2} (B)^{\alpha_3} (W)^{\alpha_4}$ (

Account	Item	Number of Units	Overall Dimensions (Space Req'd) ft. O.D. x ft. long	A External Heat Transfer Surface, ft^2	P Design Pressure psia	B Brake Horsepower, BHP	W Flowrate GPM
23.05.07	H_2O-H_2 Vapor After-Cooler of the Degassing Heaters	1	3.96 x 19.92	3,400	60		
23.05.08	Desuperheater-Condenser for Feedwater Heater	7	9.17 x 60.83	133,400	60		
23.05.09	H_2O-H_2 Vapor After-Cooler of the Feedwater Heater	7	7.83 x 42.75	69,360	60		
23.08.01	Vapor Compressor for H_2 Conditioning System, Stages 1-8	25			220	Varies with the stage	
23.08.02	Intercooler-Condenser for Hydrogen Conditioning System, Stages 1-8	8					
23.08.03	Vapor Compressors for Raw H_2 Product Conditioning-Polishing Stages 9-11	12				Varies with the stage	
23.08.04	Intercooler-Condenser for Raw H_2O Product Conditioning-Polishing, Stages 9-11	3		26,330	Varies with the stage (380 - 1150)		
23.08.05	Raw Hydrogen Product Scrubbing Tower Scrub Tower and Motor Pumps Scrub Tower Pall Rings	1 2	9.1 x 47		1150	0.53	
23.08.06	Scrub Water Evaporator	1	8 x 30	2,478			714.6
23.08.07	Drying Towers	3	9.1 x 47		1150		
23.08.08	High Temperature Electrolyzer Molecular Sieves (Resin) Drying Tower Auxiliaries	28 3	19.7 x 64		1150		

*Component Hardware Costs Only

A = External heat transfer surface area, ft^2

P = Design pressure, psia

B = Brake horsepower, HP

W = Flowrate, gpm

M = Mass, lb

β = Varies from stage to stage

5.2-1 (CONTINUED)

COEFFICIENTS, SCALE FACTORS AND COSTS FOR THE HYFIRE (TOKAMAK)

$)^{\alpha_1}$ $(P)^{\alpha_2}$ $(B)^{\alpha_3}$ $(W)^{\alpha_4}$ $(M)^{\alpha_5}$ $(Q)^{\alpha_6}$

B Brake sepower, BHP	W Flowrate GPM	M Mass, lb	Q Turbine Output, MW	Co Cost Coefficient	α_1	α_2	α_3	α_4	α_5	α_6	γ_0	Total * Cost (one or more units) $ M
				250	0.646	0.293	0	0	0		1	0.17
				516.5	0.646	0.293	0	0	0		1	24.6
				310	0.646	0.293	0	0	0		1	2.76
es with stage				1860	0	0	0.733	0	0		1	16.82
				206.6	0.646	0.293	0	0	0		1	25.82
es with stage				1860	0	0	0.733	0	0		1	11.22
				206.6 β	0.646	0.293	0	0	0			21.82
0.53		1.76×10^5		173.1 4447	0 0	0.293 0.293	0 0.78	0 0	0.63 0		1 1	2.92 0.04 0.16
	714.6			17,570	0.649	0	0	0	0		1	1.37
		1.76×10^5		173.1	0	0.292	0	0	0.63		1	8.26
		1.76×10^5		173.1	0	0.293	0	0	0.63		0.07	216.44 1.85 0.93

format. Even though all the assumptions being made by individual study groups are not identical, comparisons of some of the results can be made as long as logical judgment is used.

B. Capital Cost for HYFIRE Tokamak

The total capital cost for HYFIRE is shown in Table 5.3-1. This table was developed using STARFIRE Table 22-5, Ref. 6 (which is included in this report as Table 5.3-1) as its base. (Tables 5.3-1, 5.3-2, 5.3-3, 5.3-4, and 5.3-5 appear at the end of Section 5.) An estimate was developed for each applicable account number entry. Specific accounts, as noted below, used in STARFIRE are estimated costs with the only change being the escalation of 5% for one year from the 1980 STARFIRE to the 1981 costs for the HYFIRE Tokamak. These accounts are:

Account 20 (Land and Land Rights), 21 (Structures and Site Facilities) except for the reactor building, hot cell building, electrolyzer building, process module building and hydrogen water separation building, 24 (Electric-Plant Equipment), 25 (Miscellaneous Plant Equipment), and 26 (Special Materials).

Account 22.01 (Reactor Equipment) utilized the STARFIRE costs with modification factors of 1.5 and 2.55 used to account for the different sizes, special materials, and operating conditions. As an example, the STARFIRE blanket and first wall cost of $82.36 M was raised to $210 M for HYFIRE. The STARFIRE Magnet cost of $171.57 M was raised to $257.36 M.

Accounts 22.02 (Main Heat Transfer and Transport Systems), 23.08 (Hydrogen Conditioning System), 22.07 and 23.07 (Instrumentation and Control Equipment) were developed independently for HYFIRE.

The total direct cost for the plant including construction of $540 M ($2124 M - STARFIRE) and the total capital cost is $6108 M ($2400 M - STARFIRE)

TABLE 5.3-1

HYFIRE (TOKAMAK) CAPITAL COSTS

Account Number	Account Title	Costs (1981, $M)	
20	Land and Land Rights	3.47	
20.01	Land and Privilege Acquisition		3.15
20.02	Relocation of Buildings, Utilities, Highways, and Other Services		0.315
21	Structures and Site Facilities	501.17	
21.01	Site Improvements and Facilities		11.7
21.02	Reactor Building		57.92
21.03	Turbine Building		77.80
21.04	Cooling System Structures		7.82
21.05	Electrical Equipment and Power Supply Building		27.52
21.06	Plant Auxiliary Systems Building		3.42
21.07	Hot Cell Building		71.40
21.08	Reactor Service Building		19.63
21.09	Service Water Building		0.69
21.10	Fuel Handling and Storage Building		9.06
21.11	Control Room Building		3.26
21.12	On-Site DC Power Supply Building		2.15
21.13	Administration Building		.91
21.14	Site Service Building		.91
21.15	Cryogenics and Tritium Building		6.53
21.16	Security Building		.33
21.17	Ventilation Stack		1.90
	Hydrogen and Water Separation		9.7

TABLE 5.3-1 (Cont'd)

Account Number	Account Title	Costs (1981, $M)		
	Electrolyzer Building			103.66
	Process Module Building			31.17
21.98	Spare Parts Allowance 2%			8.94
21.99	Contingency Allowance 10%			44.75
22	Reactor Plant Equipment	2218.59		
22.01	Reactor Equipment		1186.39	
22.01.01	First Wall and Blanket			210.02
22.01.02	Shield			47[illegible].48
22.01.03	Magnets			257.36
22.01.04	RF Heating and Current Drive			50.24
22.01.05	Primary Structure and Support			79.11
22.01.06	Reactor Vacuum			12.39
22.01.07	Power Supply, Switching and Energy Storage			79.35
22.01.08	Impurity Control			6.25
22.01.09	ECRH Plasma Breakdown			7.19
22.02	Main Heat Transfer and Transport Systems		851.48	
	Helium Heat Exchangers			217.04
	Primary Helium Circulating Pumps			76.71
	Secondary Helium Circulating Pump			30.82
	Oxygen After-Cooler			2.85
	Recuperator H_2O-H_2 Units			228.47
	Oxygen Recuperator			7.98
	Boiler Superheater			279.79
	Boiler Superheater Feed Pumps			1.50

TABLE 5.3-1 (Cont'd)

Account Number	Account Title	Costs (1981, $M)	
	First Wall Pressurized H_2O Circ. Pump		6.36
22.03	Cryogenic Cooling System	22.35	
22.03.01	Helium Liquifier Refrigerator		11.55
22.03.02	LHe Transfer and Storage		5.4
22.03.03	He Gas Storage		4.2
22.03.04	LN_2 System		1.2
22.04	Radioactive Waste Treatment and Disposal	7.2	
22.02.01	Liquid Waste Processing and Equipment		2.55
22.04.02	Gaseous Wastes and Off-Gas Processing System		2.7
22.04.03	Solid Wastes Processing Equipment		1.95
22.05	Fuel Handling and Storage Systems	64.93	
22.05.01	Secondary Processing - Off Gas Treatment		7.85
22.05.01	Isotope Purification (Cryogenic Distillation)		10.18
22.05.02	Plasma Exhaust Processing		7.85
22.05.02	Processing Atmospheres Detritiation		3.12
22.05.03	Fuel Preparation		0.45
22.05.04	Fuel Injection		1.50
22.05.05	Tritium Storage		6.73
22.05.05	Deuterium Storage		2.48
22.05.06	Bred Tritium Extraction		10.90
22.05.07	Reactor Vessel Detritiation Unit		2.13
22.05.07	Reactor Hall Atmosphere Detritiation Unit		11.74
22.06	Other Reactor Plant Equipment	51.22	
22.06.01	Maintenance Equipment		43.00

TABLE 5.3-1 (Cont'd)

Account Number	Account Title	Costs (1981, $M)		
22.06.02	Special Heating Systems			0.00
22.06.03	Coolant Receiving, Storage and Make-Up Systems			0.36
22.06.04	Gas Systems			0.12
22.06.05	Inert Atmosphere System			0.00
22.06.06	Fluid Leak Detection			3.0
22.06.07	Closed Loop Coolant System			3.0
22.06.08	Standby Cooling System			1.74
22.07	Instrumentation and Control		35.02	
22.07.01	Reactor I&C Equipment			11.42
22.07.02	Monitoring Systems			2.54
22.07.03	Instrumentation and Transducers			21.06
22.98	Spare Parts Allowance 2%			48.77
22.99	Contingency Allowance 10%			243.83
23	Turbine Plant Equipment	1505.42		
23.01	Turbine-Generators			154.10
*23.02	Main Steam and Oxygen System			--
23.03	Heat Rejection Systems			78.35
23.04	Condensing Systems			105.50
**23.05	Feed Heating Systems			139.89
23.06	Other Turbine Plant Equipment			242.53

*Included in Account 22 and portions of 23.

**Items found in Account 23.05 are itemized in Table 8.4-4.

TABLE 5.3-1 (Cont'd)

Account Number	Account Title	Costs (1981, $M)	
23.07	Instrumentation and Control (I&C) Equipment		35.04
*23.08	Hydrogen Conditioning System	588.72	
23.08.01	H_2-H_2O Vapor Compressors (Stages 1-8)		23.25
23.08.02	Post Compression After-Coolers (Stages 1-8)		39.87
23.08.03	Piping, Valves, Supports, etc.		21.35
23.08.04	H_2-H_2O Vapor Compressors for Raw Hydrogen Product (Stages 9-11)		22.51
23.08.05	Post Compression After-Coolers (Stages 9-11)		46.05
23.08.06	Scrubbing Tower Canned Pumps and Pall Rings for Raw Hydrogen Product		6.71
23.08.07	Evaporator for Deactivating Scrub Water		3.10
23.08.08	Final Hydrogen Product Drying Tower and Molecular Sieve Auxiliaries		19.79
23.08.09	Electrolyzer		406.09
23.98	Spare Parts Allowance 2%		26.88
23.99	Contingency Allowance 10%		134.41
24	<u>Electric Plant Equipment</u>	118.67	
24.01	Switchgear		13.0
24.02	Station Service Equipment		17.89
24.03	Switchboards		8.19
24.04	Protective Equipment		2.22
24.05	Electrical Structures and Wiring Containers		18.27
24.06	Power and Control Wiring		37.79
24.07	Electrical Lighting		8.61

*Not included in normal account number system.

TABLE 5.3-1 (Cont'd)

Account Number	Account Title		Costs (1981, $M)	
24.98	Spare Parts Allowance 4%			2.12
24.99	Contingency Allowance 10%			10.60
25	Miscellaneous Plant Equipment		46.19	
25.01	Transportation and Lifting Equipment			20.24
25.02	Air and Water Service Systems			12.97
25.03	Communications Equipment			6.53
25.04	Furnishing and Fixtures			0.78
25.98	Spare Parts Allowance 3%			1.62
25.99	Contingency Allowance 10%			4.05
26	Special Materials		0.25	
	TOTAL DIRECT COST		4393.76	
91	Construction Facilities, Equipment and Services (10%)		439.38	
92	Engineering and Construction Management Services (8%)		351.50	
93	Other Costs - Owners (5%)		219.69	
	SUBTOTAL		5404.33	
		1981 Constant	1987 Then-Current	
94	Interest During Construction	704.18	1709.39	
95	Escalation During Construction	0.00	1024.66	
	TOTAL CAPITAL	6108.51	8138.38	
	$/#$H_2$	.66	1.27	
	$/MBtu H_2	10.74	20.88	

TABLE 5.3-2
HYFIRE (TOKAMAK) CAPITAL COSTS
(ABBREVIATED)

Account Number	Account Title	Costs (1981, $M)	
20	Land and Land Rights	3.47	
20.01	Land and Privilege Acquisition		3.15
20.02	Relocation of Buildings, Utilities, Highways, and Other Services		0.315
21	Structures and Site Facilities	447.48	
21.01	Site Improvements and Facilities		11.7
21.02	Reactor Building		57.92
21.03	Turbine Building		77.80
21.04	Cooling System Structures		7.82
21.05	Electrical Equipment and Power Supply Building		27.52
21.06	Plant Auxiliary Systems Building		3.42
21.07	Hot Cell Building		71.40
21.08	Reactor Service Building		19.63
21.09	Service Water Building		0.69
21.10	Fuel Handling and Storage Building		9.06
21.11	Control Room Building		3.26
21.12	On-Site DC Power Supply Building		2.15
21.13	Administration Building		.91
21.14	Site Service Building		.91
21.15	Cryogenics and Tritium Building		6.53
21.16	Security Building		.33
21.17	Ventilation Stack		1.90
	Hydrogen and Water Separation		9.7

TABLE 5.3-2 **(Cont'd)**

Account Number	Account Title	Costs (1981, $M)		
	Electrolyzer Building			103.66
	Process Module Building			31.17
22	Reactor Plant Equipment	1925.99		
22.01	Reactor Equipment		1186.39	
22.01.01	First Wall and Blanket			210.02
22.01.02	Shield			474.48
22.01.03	Magnets			257.36
22.01.04	RF Heating and Current Drive			50.24
22.01.05	Primary Structure and Support			79.11
22.01.06	Reactor Vacuum			12.39
22.01.07	Power Supply, Switching and Energy Storage			79.35
22.01.08	Impurity Control			6.25
22.01.09	ECRH Plasma Breakdown			7.19
22.02	Main Heat Transfer and Transport Systems		851.48	
	Helium Heat Exchangers			217.04
	Primary Helium Circulating Pump			76.71
	Secondary Helium Circulating Pump			30.82
	Oxygen After-Cooler			2.85
	Recuperator H_2O-H_2 Units			228.47
	Oxygen Recuperator			7.98
	Boiler Superheater			279.79
	Boiler Superheater Feed Pump			1.50
	First Wall Pressurized H_2O Circ. Pump			6.36

TABLE 5.3-2 (Cont'd)

Account Number	Account Title	Costs (1981, $M)	
22.03	Cryogenic Cooling System	22.35	
22.03.01	Helium Liquifier Refrigerator		11.55
22.03.02	LHe Transfer and Storage		5.4
22.03.03	He Gas Storage		4.2
22.03.04	LN_2 System		1.2
22.04	Radioactive Waste Treatment and Disposal	7.2	
22.02.01	Liquid Waste Processing and Equipment		2.55
22.04.02	Gaseous Wastes and Off-Gas Processing System		2.7
22.04.03	Solid Wastes Processing Equipment		1.95
22.05	Fuel Handling and Storage Systems	64.93	
22.05.01	Secondary Processing - Off Gas Treatment		7.85
22.05.01	Isotope Purification (Cryogenic Distillation)		
22.05.02	Plasma Exhaust Processing		7.85
22.05.02	Processing Atmospheres Detritiation		3.12
22.05.03	Fuel Preparation		
22.05.04	Fuel Injection		
22.05.05	Tritium Storage		6.73
22.05.05	Deuterium Storage		2.48
22.05.06	Bred Tritium Extraction		10.90
22.05.07	Reactor Vessel Detritiation Unit		2.13
22.05.07	Reactor Hall Atmosphere Detritiation Unit		11.74
22.06	Other Reactor Plant Equipment	51.22	
22.06.01	Maintenance Equipment		43.00

TABLE 5.3-2 (Cont'd)

Account Number	Account Title	Costs (1981, $M)		
22.06.02	Special Heating Systems			0.00
22.06.03	Coolant Receiving, Storage and Make-Up Systems			0.36
22.06.04	Gas Systems			0.12
22.06.05	Inert Atmosphere System			0.00
22.06.06	Fluid Leak Detection			3.0
22.06.07	Closed Loop Coolant System			3.0
22.06.08	Standby Cooling System			1.74
22.07	Instrumentation and Control		35.02	
22.07.01	Reactor I&C Equipment			11.42
22.07.02	Monitoring Systems			2.54
22.07.03	Instrumentation and Transducers			21.06
23	Turbine Plant Equipment	1344.13		
23.01	Turbine-Generators			154.10
*23.02	Main Steam and Oxygen System			--
23.03	Heat Rejection Systems			78.35
23.04	Condensing Systems			105.50
23.05	Feed Heating Systems			139.89
23.06	Other Turbine Plant Equipment			242.53
23.07	Instrumentation and Control (I&C) Equipment			35.04
**23.08	Hydrogen Conditioning System		578.19	
23.08.01	H_2-H_2O Vapor Compressors (Stages 1-8)			23.25

*Included in portions of Accounts 22 and 23.

**Not included in normal account number system.

TABLE 5.3-2 (Cont'd)

Account Number	Account Title		Costs (1981, $M)
23.08.02	Post Compression After-Coolers (Stages 1-8)		39.87
23.08.03	Piping, Valves, Supports, etc.		21.35
23.08.04	H_2-H_2O Vapor Compressor for Raw Hydrogen (Stages 9-11)		22.51
23.08.05	Post Compression After-Coolers (Stages 9-11)		46.05
23.08.06	Scrubbing Tower Canned Pumps and Pall Rings for Raw Hydrogen Product		6.71
23.08.07	Evaporator for Deactivating Scrub Water		3.10
23.08.08	Final Hydrogen Product Drying Tower and Molecular Sieve Auxiliaries		19.79
23.08.09	Electrolyzer		406.09
24	Electric Plant Equipment	105.95	
24.01	Switchgear		13.0
24.02	Station Service Equipment		17.89
24.03	Switchboards		8.19
24.04	Protective Equipment		2.22
24.05	Electrical Structures and Wiring Containers		18.27
24.06	Power and Control Wiring		37.79
24.07	Electrical Lighting		8.61
25	Miscellaneous Plant Equipment	40.52	
25.01	Transportation and Lifting Equipment		20.24
25.02	Air and Water Service Systems		12.97

TABLE 5.3-2 (Cont'd)

Account Number	Account Title	Costs (1981, $M)	
25.03	Communications Equipment		6.53
25.04	Furnishing and Fixtures		0.78
26	Special Materials	0.25	
	TOTAL DIRECT COST	3873.48	

	1981 Constant
$/# H_2	.44
$/MBtu H_2	7.14

TABLE 5.3-3

STARFIRE CAPITAL COSTS*

Account Number	Account Title	Costs (1980, $M)	
20	Land and Land Rights	3.30	
20.01	Land and Privilege Acquisition		3.0
20.02	Relocation of Buildings, Utilities, Highways, and Other Services		0.3
21	Structures and Site Facilities	346.58	
21.01	Site Improvements and Facilities		11.15
21.02	Reactor Building		157.44
21.03	Turbine Building		35.92
21.04	Cooling System Structures		7.96
21.05	Electrical Equipment and Power Supply Building		9.16
21.06	Plant Auxiliary Systems Building		3.26
21.07	Hot Cell Building		53.69
21.08	Reactor Service Building		1.88
21.09	Service Water Building		0.66
21.10	Fuel Handling and Storage Building		8.63
21.11	Control Room Building		3.10
21.12	On-Site DC Power Supply Building		2.05
21.13	Administration Building		0.87
21.14	Site Service Building		0.87
21.15	Cryogenics and Inert Gas Storage Building		0.91
21.16	Security Building		0.31
21.17	Ventilation Stack		1.81

*Taken from Reference 6

TABLE 5.3-3 (Cont'd)

Account Number	Account Title	Costs (1981, $M)		
21.98	Spare Parts Allowance		1.96	
21.99	Contingency Allowance		44.95	
22	Reactor Plant Equipment	968.62		
22.01	Reactor Equipment		589.26	
22.01.01	Blanket and First Wall			82.36
22.01.02	Shield			186.07
22.01.03	Magnets			171.57
22.01.04	RF Heating and Current Drive			33.49
22.01.05	Primary Structure and Support			52.74
22.01.06	Reactor Vacuum			4.86
22.01.07	Power Supply, Switching and Energy Storage			52.90
22.01.08	Impurity Control			2.45
22.01.09	ECRH Plasma Breakdown			2.82
22.02	Main Heat Transfer and Transport Systems		69.84	
22.02.01	Primary Coolant System			63.10
22.02.02	Intermediate Coolant System			-
22.02.03	Limiter Cooling System			6.19
22.02.04	Residual Heat Removal System			0.55
22.03	Cryogenic Cooling System		14.90	
22.03.01	Helium Liquifier Refrigerator			7.70
22.03.02	LHe Transfer and Storage			3.60
22.03.03	He Gas Storage			2.80
22.03.04	LN_2 System			0.80

TABLE 5.3-3 (Cont'd)

Account Number	Account Title	Costs (1981, $M)	
22.04	Radioactive Waste Treatment and Disposal	4.80	
22.04.01	Liquid Waste Processing and Equipment		1.70
22.04.02	Gaseous Wastes and Off-Gas Processing System		1.80
22.04.03	Solid Wastes Processing Equipment		1.30
22.05	Fuel Handling and Storage Systems	38.60	
22.05.01	Fuel Purification Systems		8.80
22.05.02	Liquefaction		-
22.05.03	Fuel Preparation Systems		0.30
22.05.04	Fuel Injection		1.40
22.05.05	Fuel Storage		2.00
22.05.06	Tritium Extraction and Recovery		5.40
22.05.07	Atmospheric Tritium Recovery System		20.70
22.06	Other Reactor Plant Equipment	43.75	
22.06.01	Maintenance Equipment		38.30
22.06.02	Special Heating Systems		0.00
22.06.03	Coolant Receiving, Storage and Make-Up Systems		0.24
22.06.04	Gas Systems		0.08
22.06.05	Inert Atmosphere System		0.00
22.06.06	Fluid Leak Detection		2.00
22.06.07	Closed Loop Coolant System		1.97
22.06.08	Standby Cooling System		1.16
22.07	Instrumentation and Control	23.41	
22.07.01	Reactor I&C Equipment		7.61
22.07.02	Monitoring Systems		1.76

TABLE 5.3-3 (Cont'd)

Account Number	Account Title	Costs (1981, $M)		
22.07.03	Instrumentation and Transducers			14.04
22.98	Spare Parts Allowance		66.38	
22.99	Contingency Allowance		117.68	
23	Turbine Plant Equipment	249.68		
23.01	Turbine-Generators		77.33	
23.02	Main Steam System		4.37	
23.03	Heat Rejection Systems		44.34	
23.04	Condensing Systems		19.18	
23.05	Feed Heating Systems		9.39	
23.06	Other Turbine Plant Equipment		50.84	
23.07	Instrumentation and Control (I&C) Equipment		8.70	
23.98	Spare Parts Allowance		3.41	
23.99	Contingency Allowance		32.12	
24	Electric Plant Equipment	117.28		
24.01	Switchgear		12.39	
24.02	Station Service Equipment		17.04	
24.03	Switchboards		7.80	
24.04	Protective Equipment		2.11	
24.05	Electrical Structures and Wiring Containers		17.40	
24.06	Power and Control Wiring		35.99	
24.07	Electrical Lighting		8.20	
24.98	Spare Parts Allowance		1.21	
24.99	Contingency Allowance		15.14	

TABLE 5.3-3 (Cont'd)

Account Number	Account Title	Costs (1981, $M)		
25	Miscellaneous Plant Equipment		40.77	
25.01	Transportation and Lifting Equipment			15.68
25.02	Air and Water Service Systems			12.35
25.03	Communications Equipment			6.22
25.04	Furnishing and Fixtures			0.75
25.98	Spare Parts Allowance			0.52
25.99	Contingency Allowance			5.25
26	Special Materials		0.25	
	TOTAL DIRECT COST		1726.48	
91	Construction Facilities, Equipment and Services (10%)		172.65	
92	Engineering and Construction Management Services (8%)		138.12	
93	Other Costs -(5%)		86.32	
	SUBTOTAL		2123.57	
		1980 Constant	1986 Then-Current	
94	Interest During Construction	276.70	671.69	
95	Escalation During Construction	0.00	402.63	
	TOTAL CAPITAL	2400.27	3197.89	
	$/kWe	2000	2665	

TABLE 5.3-4

HYFIRE TOKAMAK COST ANALYSIS

ACCOUNT 23 TURBINE PLANT EQUIPMENT

23.05 FEEDHEATING SYSTEM

No. of Units	Component	Total Cost in $M
2	Oxygen After Cooler Cooling Water Circulating Pump	0.310
5	Water Feed to Feed Preheater Circulating Pump	2.02
6	Boiler Superheater Circulating Pump	2.83
5	Make-up and Recycle Water Circulating Pump	.821
4	Feed Preheater	68.92
4	Desuperheater Condensers for Degassing Heater	13.22
1	H_2O-He Vapor After Cooler for Degassing Heater	.371
7	Desuperheating Condensers for Feedwater Heater	46.13
2	H_2O-He Vapor After Cooler for Feedwater Heater	5.27
	TOTAL	139.892

TABLE 5.3-5

VALUES FOR F_{IDC} AND F_{EDC}

Construction Period (Yr)	Constant Dollar Economic Analysis Mode (Assumed Cost of Capital = 5%/year) (Escalation Rate = None)		Current Dollar Economic Analysis Mode (Assumed Cost of Capital = 10%/Year) (Escalation Rate = 5%/Year)	
	F_{IDC}	F_{EDC}	F_{IDC}	F_{EDC}
4	.081	-0-	.191	.122
5	.108	-0-	.251	.155
6	.129	-0-	.316	.190
7	.152	-0-	.388	.225
8	.170	-0-	.466	.261
9	.192	-0-	.551	.229
10	.221	-0-	.644	.338

in constant 1981 dollars and \$8138.38 M (\$3198 M-STARFIRE) in the then current 1987 dollars. These estimates result in the cost of hydrogen for HYFIRE to be \$10.74/MBtu in 1981 constant dollars utilizing a plant availability factor of 80%.

Since the plant will be the tenth-of-a-kind with the majority of the design and construction problems resolved, an abbreviated Table 5.3-2 is also developed which is limited to Accounts 20, 21, 22, 23, 24, 25, and 26 and with the spare parts and contingency allowances eliminated.

In Table 5.3-2, it is seen that the total direct cost is \$3873 M with the cost of hydrogen coming to \$7.14/MBtu. This cost compares competitively with the price of hydrogen generated from natural gas and coal which ranges from \$4.00 to \$7.00/MBtu.

C. Cost Drivers

1. The total cost is naturally determined from the sum of the various input items. Some of these individual high-cost drivers (Table 5.3-1) are found to be located as follows: Account No. 21, Structures and Site Facilities, (\$501.17 M for HYFIRE and \$346.58 M for STARFIRE), Account No. 22, Reactor Plant Equipment, (\$2218.59 M for HYFIRE and \$968.62 M for STARFIRE), and Account No. 23, Turbine Plant Equipment (\$1505.42 M for HYFIRE and \$249.68 M for STARFIRE).

2. The HYFIRE system has four buildings which require heavily shielded construction similar to the reactor building.

	HYFIRE Tokamak Cost Estimate	STARFIRE Cost Estimate
Reactor Building	\$ 57.92 M	\$157.44 M
Hot Cell Building	\$ 71.40 M	\$ 53.69 M
Electrolyzer Building	\$103.66 M	\$ ---
Process Module Building	\$ 31.17 M	\$ ---
TOTAL	\$264.15 M	\$211.13 M

This additional \$53.02 M is brought about by the fact that the reactor is larger and the electrolyzer and recuperators (which were not part of STARFIRE) must be located as close to the reactor as possible to minimize the large expense due to the high temperature piping connecting the reactor blankets to the electrolyzers and to the recuperators (see Fig. 4.3-1).

3. The higher cost components in the Reactor Plant Equipment grouping are:

	ESTIMATED COST	
Component	HYFIRE Tokamak (M)	STARFIRE (M)
Blanket and First Wall	\$ 210.02	\$ 82.36
Shield	\$ 474.48	\$186.07
Magnets	\$ 257.36	\$121.57
rf Heating and Current Drive	\$ 50.24	\$ 33.49
Primary Support Structure	\$ 79.11	\$ 32.74
Power Supply	\$ 79.35	\$ 52.90
Helium Heat Exchangers	\$ 217.04	\$ ---
Primary Helium Circulation Pumps	\$ 76.71	\$ ---
Secondary Helium Circulating Pumps	\$ 30.82	\$ ---
Oxygen After-cooler	\$ 2.85	\$ ---
Recuperators at H_2O-He	\$ 228.47	\$ ---
Oxygen Recuperator	\$ 7.98	\$ ---
Boiler Superheater	\$ 279.79	\$ ---
Boiler Superheater Feed Pumps	\$ 1.50	\$ ---
First Wall Pressurized H_2O Circulating Pumps	\$ 6.36	\$ ---
TOTAL	\$2002.08	\$509.13

The additional cost of $1493 M for HYFIRE over STARFIRE is brought about by two main factors. The first is the result of scaling up the cost of the first five items to provide for the higher thermal power (6000 MW(th) rather than 3500 MW(th)), and the assumed requirements of using much more expensive material and fabrication for the blanket than was used for STARFIRE due to the higher temperatures and more complicated design. The second major cost driver is the additional nine items of equipment (He heat exchangers, etc.) which have been estimated to cost approximately $852 M. Again, it should be noted that no firm design exist for these equipment components so that the cost is an estimate which would be changed once additional analysis and design have been completed.

4. The higher cost components in the Turbine Plant Equipment grouping are:

ESTIMATED COST

Component	HYFIRE Tokamak (M)	STARFIRE (M)
Turbine Generators	$ 154.10	$ 77.33
Main Steam System	$ ---	$ 4.37
Heat Rejection Systems	$ 78.35	$ 44.34
Condensing Systems	$ 105.50	$ 19.18
Feed Heating Systems	$ 139.89	$ 9.89
Other Turbine Plant Equipment	$ 242.53	$ 50.84
Instrumentation and Control	$ 35.04	$ 9.70

ESTIMATED COST (Continued)

Hydrogen Condition System		
H_2-H_2O Vapor Comp. (Stages 1-8)	$ 23.25	$ ---
Post Comp. After-cooler (Stages 1-8)	$ 39.87	$ ---
Piping, Valves, Supports	$ 21.35	$ ---
H_2-H_2O Vapor Comp. (Stages 9-11)	$ 22.51	$ ---
Post Comp. After-coolers (Stages 9-11)	$ 46.05	$ ---
Scrubbing Tower, Canned Pumps and Pall Rings for Raw Hydrogen	$ 6.71	$ ---
Evaporator for Deactivating Scrub Water	$ 3.10	$ ---
Final Hydrogen Product Drying Towers and Molecular Sieve Auxiliaries	$ 19.97	$ ---
Electrolyzer	$ 406.09	$ ---
TOTAL	$1344.31	$214.15

The additional cost of $1130 M for HYFIRE over and above that of STARFIRE is due to various factors. All of the hydrogen conditioning system cost ($589 M) is unique to HYFIRE. The difference in the turbine cost is partially due to the fact that HYFIRE has three turbines while STARFIRE has only one. Other contributors to the difference are the following:

a) The presence of substantial amounts of hydrogen in the steam leads to equipment complications and low overall heat transfer coefficients.

b) Stemming from the design goal of keeping the dimensions and weights of the equipment within the capacity of the cranes, monorail handling devices, and maintenance facilities; many smaller units are specified as a rule instead of one or a few large units.

c) In addition to losing the cost advantage resulting from fewer and larger equipment items, the multiplicity complicates and substantially increases the piping and installation cost.

d) The low-pressure turbine's feed is a steam-hydrogen mixture with a 0.099 mole H_2/H_2O ratio for HYFIRE which is in contrast to the usual design for fusion reactor-driven electric power plants which normally operate only on steam.

e) The feed-water system is also much more complicated than in a normal reactor plant. Since there is a large amount of hydrogen included in the turbine extraction stream, numerous additional components are required for the system.

D. Contingency and Spare Parts Allowances

1. Contingency

As noted in Ref. 2, the contingency allowance is an amount added to an estimate and the total amount that is reasonably expected to be spent, considering the degree of uncertainties in the estimated quantities, prices, labor productivity, etc. embodied in the detailed estimates. The contingency allowance is added to an estimate to reduce the risk of overrun to an acceptable level. For the conceptual level of design for fusion plant Accounts 21, 22, 23, 24, and 25, a contingency allowance of 15% of estimated cost is recommended. Since HYFIRE is assumed to be the tenth-of-a-kind plant, it is feasible to lower this contingency allowance. HYFIRE and STARFIRE use 10% for Accounts 21, 22, 23, 24, and 25.

2. Spare Parts

Reference 25 indicates that the type and number of spare parts to be provided in inventory at the start-up of a power plant is decided by the owner of the plant. Common practice indicates that a reasonable cost allowance for the value of spares in inventory falls in a fairly consistent range of percentages of major equipment costs. This allowance may also be expressed as a function of total cost of installed equipment, since the relationship between major equipment cost and total cost of equipment and materials remain relatively constant.

HYFIRE has used Refs. 1 and 2 recommended spare parts as indicated below:

Account Number	Spare Parts Allowance
21, 22, 23	2%
24	4%
25	3%

These percentages do not account for any permanently installed spare components which can be employed by the opening and closing of electrical switches and valves. The cost of permanently installed spare units is included in the cost of components.

E. Indirect Cost

Reference 3 discusses the philosophy of indirect costs for Accounts 91 (Construction Facilities, Equipment, and Services), 92 (Engineering and Construction Management Services), and 93 (Owners). HYFIRE has utilized the percentages which were rationalized for the STARFIRE Report as noted.

Account Number	Percentage of Direct Cost
91	10
92	8
93	5

F. Time-Related Costs

Reference 1 shows that the two time-related costs are the interest cost during construction (Account 94), and the cost of escalation during construction (Account 95). When using a current dollar economic analysis mode, both should be computed with a reference 10%/year nominal cost of capital, and a reference 5%/year escalation rate. When using a constant dollar analysis mode, interest during construction cost should be computed with a reference 5%/year deflated (real) cost of capital and escalation during construction cost should not be computed.

The following equations should be used to estimate time-related costs. Equations are based on the expenditure pattern shown in Table 5.3-5.

Interest During Construction (Account 94) Cost = Total Direct Capital Cost + Total Indirect Capital Cost x F_{IDC}

Escalation During Construction (Account 95) Cost = Total Direct Capital Cost + Total Indirect Capital Cost x F_{EDC}

Values for F_{IDC} and F_{EDC} using the reference financing assumptions are given in Table 5.3-5--Values for F_{IDC} and F_{EDC}. (This was Table 2 in Ref. 1.) The period required to design, construct, and start up the facility is the period during which time related costs will be incurred. This period is known as the construction period. HYFIRE has used the same construction period as STARFIRE, six years.

G. Cost of Hydrogen

Reference 1 describes the means to determine the total busbar energy cost of the total electricity cost. It indicates that the total cost of energy from a fusion reactor electricity producing facility is to be computed as a function of the following components:

1. Plant availability factor;
2. Financial assumptions;
3. Fixed charge rate;
4. Capital cost;
5. Annual operating and maintenance cost;
6. Annual scheduled component replacement cost;
7. Annual fuel cost; and
8. Plant capacity .

These same components are required to determine the cost of hydrogen which the plant produces. Therefore, the formulas developed in Ref. 1 for total busbar energy cost can be used to estimate the total cost of hydrogen by changing the PC (Plant Capacity) from kWh/yr to #H_2/yr.

The Ref. 1 formulas for Total Busbar Energy Cost for both the current dollar economic analysis mode and the constant dollar economic analysis mode are given below.

1. Constant Dollar Economic Analysis Mode

The constant dollar economic analysis mode assumed general inflation rates and escalation rates are equal to zero. The equation that should be used to determine total energy cost is as follows:

$$\text{Total Busbar Energy Cost (mills/kWh)} = \frac{C_c(fcr) + C_{o\&m} + C_{scr} + C_F}{(Pc)\ (PAF)\ (10^{-3})}$$

where:

C_c = facility capital cost (dollars),

fcr = annual fixed charge rate (= .10),

$C_{o\&m}$ = annual operating and maintenance cost (dollars),

C_F = Annual fuel cost (dollars),

C_{scr} = annual scheduled component replacement cost (dollars),

PC = plant capacity (kWh/yr), and

PAF = plant availability factor (= %/100).

The plant capacity for the HYFIRE Tokamak is 145000 #H_2/hr or 1270 x 10^6#H_2/yr.

2. Current Dollar Economic Analysis Mode

The current dollar economic analysis mode assumes that general inflation and escalation will occur. Costs are escalated to reflect this assumption. The total busbar energy cost figure is a nominal or actual first year busbar energy cost. For this reason, annual operating and maintenance costs, annual scheduled component replacement costs, and annual fuel costs that were estimated using preconstruction year price levels are escalated to first year of facility operation price levels. The equation that should be used to determine total busbar energy cost is as follows:

$$\begin{array}{l}\text{Total Busbar Energy Cost}\\ \text{(mills/kWh)}\end{array} = \frac{C_c(fcs) + C_{o\&m}(E+1)^P + C_{scr}(E+1)^P + C_f(E+1)^P}{(PC)\ (PAF)\ (10^{-3})}$$

where

C_c = facility capital cost (dollars),

fcr = annual fixed charge rate (= .15),

$C_{o\&m}$ = annual operating and maintenance cost (dollars),

E = annual escalation rate (= .05),

P = construction period (years),

C_{scr} = annual scheduled component replacement cost (dollars),

C_f = annual fuel cost (dollars),

PC = plant capacity (kWh/yr), and

PAF = plant availability factor (= %/100).

HYFIRE used the STARFIRE Report (Ref. 6) estimates (escalated) as the basis for the following:

a) annual operating and maintenance,

b) annual fuel cost, and

c) annual scheduled component replacement cost. (HYFIRE Component Cost Used).

The plant availability factor was taken as 80%.

ACKNOWLEDGEMENTS

The editor acknowledges the contribution made by those listed at the beginning of the Report. He also wishes to express his deep appreciation to Mrs. Eleanor Dahl and Ms. Jeanne Danko for preparation and typing of the manuscript.

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APPENDIX A

PERFORMANCE OF THE HIGH-TEMPERATURE ELECTROLYZER TUBES

The performance of the high-temperature electrolyzer using current and future technology can be estimated from fuel cell tube design data developed for high-temperature solid oxide fuel cells. The present-day technology consists of materials and construction extended to active tube lengths of 1.56 meters. Operating conditions for the electrolyzer tubes are defined by inlet steam temperature, by flow rate, and by the current density, coupled with electrolyzer-tube geometry and materials of construction. Conversely, the steam temperature and molal ratio of inlet-steam-to-product hydrogen and the current density will define the operating conditions. An examination of operating performance and its electrolyzer efficiency follows.

Tube Geometry and Materials

The present fuel cell tube geometry consists of concentric electrolyzer elements that are one centimeter in length. Each element is connected in series to its two contiguous elements, such that the element-to-element spacing is 1 1/4 centimeters. For convenience, this analysis deals with an electrolyzer element geometry that places the oxygen electrode on the inside of the tube and the hydrogen electrode on the outside of the tube, i.e., the steam (and hydrogen) flow occurs on the shell-side of the electrolyzer and the oxygen flows within the electrolyzer tubes. The geometry is best described by the two schematics shown in Figs. 2.1-1 and 2.1-2 (Section 2 of this report) with the above proviso that the detail shown in Fig. A-1 has the O_2 electrode and H_2 electrode exchanged. Tube and cell geometry characteristics are listed below:

Tube Geometry

Support tube, i.d.	1.070	cm
Support tube, o.d.	1.270	cm
Oxygen electrode, o.d.	1.410	cm
Electrode, o.d.	1.418	cm
Hydrogen electrode, o.d.	1.438	cm
Length	156	cm

Cell Geometry

Length per cell	1.000	cm
Interconnect space	0.250	cm
Cells per tube	125	
Mean electrolyte area	4.442	cm^2

The tube material is described by its electrical resistivity.

All polarization effects are disregarded; the diffusion polarizations are not very large compared with the resistivity effect and slow polarization at tube temperatures of 1100°C and above can be neglected. The tube material is presently constrained to tube temperatures below, and at 1100°C, but future developments will likely permit operation at temperatures up to 1200°C (1473 K). The resistivity of the four tube components are given below:

ρ(electrolyte) = 2.95×10^{-3} Exp (10,350/T), Ωcm

ρ(O_2 electrode) = 8.11×10^{-3} Exp (600/T), Ωcm

ρ(H_2 electrode) = 2.98×10^{-3} Exp (-1392/T), Ωcm

ρ(interconnect) = 1.26×10^{-3} Exp (4690/T), Ωcm

Resistance of each component is computed as follows:

$$R(\text{electrolyte}) = \rho_e \frac{.004 \text{ cm}}{\pi \times 1.414 \text{ cm} \times 1.000 \text{ cm}}$$

$$R(O_2 \text{ electrode}) = \rho_a \frac{(1.25/2) \text{ cm}}{\pi \times 1.340 \text{ cm} \times 0.07 \text{ cm}}$$

$$R(H_2 \text{ electrode}) = \rho_c \frac{(1.25/2) \text{ cm}}{\pi \times 1.428 \text{ cm} \times 0.01 \text{ cm}}$$

$$R(\text{interconnect}) = \rho_i \frac{.004 \text{ cm}}{\pi \times 1.414 \text{ cm} \times 0.250 \text{ cm}}$$

Resistance values for further computation were selected at 1273 K and 1423 K. (See Table A-1.)

1273 K ΣR_i = 6.85-02 Ω

1423 K ΣR_i = 5.82-02 Ω

Thermodynamic Functions

The electrolysis of water is described by the enthalpy and Gibbs-free energy change for the reaction:

$$H_2(g) + 1/2\ O_2(g) = H_2O(g) \quad .$$

The standard Gibbs-free energy and standard enthalpy are given by

$$\Delta G° = -57{,}410 + 0.94\ T \ln T + 1.65 \times 10^{-3}\ T^2 \quad .$$

$$-3.7 \times 10^{-7}\ T^3 + 3.92\ T, \text{ (cal/gmol, K)} \quad .$$

$$\Delta H° = 57{,}410 - 0.94\ T - 1.65 \times 10^{-3}\ T^2$$

$$+ 7.4 \times 10^{-7}\ T^3, \text{ (cal/gmol, K)} \quad .$$

The Gibbs free energy is given by

$$\Delta G = \Delta G° + RT \ln K_p + RT \ln p \ ,$$

TABLE A-1

COMPONENT RESISTANCE OF CELL, Ω(ohms)

Component	1273 K	1373 K	1473 K	1573 K
Electrolyte	9.015-03	4.987-03	2.989-03	1.912-03
Anode (O_2)	2.757-02	2.664-02	2.586-02	2.520-02
Cathode	1.391-02	1.506-02	1.614-02	1.714-02
Interconnect	1.801-02	1.377-02	1.092-02	8.920-03
ΣR_i	6.850-02	6.046-02	5.591-02	5.317-02

where:

$$K_p = \frac{n_{H_2O}}{n_{H_2}\sqrt{n_{O_2}}}\frac{1\ \text{atm}}{\sqrt{P_t}}$$

(R, cal/gmol K; T, K; P_t, atm; n, mol fraction).

For tube operation, P_t = 34 atm and 11% of the steam will electrolyze to H_2 and 1/2 O_2. The mol fraction values are:

$$0.00 \leq n_{H_2} \leq 0.11$$

$$0.89 \leq n_{H_2} \leq 1.00$$, (these are on the shell-side), and

$$n_{O_2} = 1.00$$, (this is inside the tube) .

The Nernst voltage for $0.00 \leq n_{H_2} \leq 0.11$ was computed from:

$$E = -\frac{\Delta G}{2 \times 96500} \times 4.184 \frac{\text{watt sec mol}}{\text{cal Coulomb}}$$, (E-volts, ΔG, cal/gmol)

Values for pertinent data at 1273 K follow, with the note that in the 1273 K calculation, polarization effects, not accounted for in this calculation, will reduce cell (and tube) performance with increased i^2R losses and higher Nernst voltages than those indicated here. The 1273 K case, as calculated in Table A-2, is included to indicate upper-bound performance of a low-temperature tube.

TABLE A-2

GIBBS FREE ENERGY AND NERNST VOLTAGES

Temp. (K)	$\Delta G°$ (cal/g-mol H_2O)	$-1/2\ RT \ln p_t$ (cal/g-mol H_2O)	E(volts), at n_{H_2} (mol)							
			.003	.007	.010	.030	.050	.070	.090	0.11
1273	-41954	-4467	.6875	.7342	.7540	.8155	.8427	.8643	.8703	.8915
1423	-39884	-4993	.6115	.6679	.6900	.7587	.7913	.8132	.8300	.8437

The average cell voltage along the tube length is approximated by:

$$\bar{E} = \frac{\int_{0.00}^{0.11} E\,dn}{\int_{0.00}^{0.11} dn} ,$$

from which

$\bar{E} \approx .85$ volts, at 1273 K,

$\bar{E} \approx .80$ volts, at 1423 K.

The values of ΔH and $\Delta H/\Delta G$ are computed below

$\Delta H = -59{,}754$ cal/g-mol (of steam, at 1273 K)

$\Delta H = -59{,}956$ cal/g-mol (of steam, at 1423 K)

$\overline{\Delta G} = -39{,}054$ cal/g-mol (of steam, at 1273 K)

$\overline{\Delta G} = -36{,}870$ cal/g-mol (of steam, at 1423 K)

$\Delta H/\overline{\Delta G} = 1.530$, (at 1273 K)

$\Delta H/\overline{\Delta G} = 1.626$, (at 1423 K)

Tube Performance

The thermal and electrical performance of the tube can be calculated from the data of the earlier sections. An 11% decomposition of steam requires a change in enthalpy of:

$\Delta h = -6{,}573$ cal/gmol (of steam, at 1273°K)

$\Delta h = -6{,}595$ cal/gmol (of steam, at 1423°K)

The tube performance will vary with current density, as indicated in Table A-3, with the calculation of i^2R given by:

$$i^2Rn = (j^2)\ (4.44\ cm^2)^2\ R \times n$$

where

j = current density, amps/cm^2,

R = cell resistance cm ΣR_i of Table A-1), and

n = 125 cells/tube.

The electrolysis energy is given by:

$$\Delta\dot{g} = \bar{E}\ j\ \ .44\ cm^2/\text{cell} \times 125\ \text{cells/tube}$$

$\Delta\dot{g}$, (rate of Gibbs-free energy change)

$$\Delta\dot{h} = \frac{\Delta H}{\Delta G}\ \Delta\dot{g}$$

$\Delta\dot{h}$, (rate of enthalpy change)

With i^2Rn loss less than $\Delta\dot{h} - \Delta\dot{g}$, heat must be added to the tube electrolysis reaction by convection from the steam.

$$\dot{q} = \Delta\dot{h} = \Delta\dot{g} - i^2Rn$$

The case may exist, but not here, where q must be removed from the electrolysis tube; this occurs if the i^2R loss exceeds $\Delta h - \Delta g$.

The calculations at two temperature levels follows:

The steam flow rate ($\dot{m}$) is calculated by

$$\dot{m} = \left(\frac{\Delta\dot{h}}{\Delta h}\right),$$ (all data at 1273 K for Table A-3 and at 1423 K for Table A-4).

The temperature fall of the steam-hydrogen mixture is calculated by:

$$\delta T = \frac{\dot{q}}{\dot{m}\ \$},$$ \$ = 9.032 cal/g-mol K, 1273 K, and 9.179 cal/g-mol K; 1423 K.

TABLE A-3

TUBE PERFORMANCE AT 1273 K

Parameter	$j=0.5\ a/cm^2$	0.4	0.3	0.2
$\Delta\dot{h}$ (cal/sec)	85.9	68.8	51.5	34.4
$\Delta\dot{g}$ (cal/sec)	56.2	44.9	33.7	22.5
i^2R (cal/sec)	10.1	6.5	3.6	1.6
$\dot{q}$ (cal/sec)	19.7	17.4	14.2	10.3
$\dot{m}$ (g-mol H_2O/sec)	1.3-02	1.0-02	0.78-02	0.52-02
δT (K)	136.0	155.0	173.0	191.0
$\dfrac{\Delta\dot{g} + i^2R^*}{\Delta\dot{g}}$	1.2	1.1	1.1	1.1

* Also, this equals the ratio of averge cell voltage to average Nernst voltage, e.g., at $j=0$ amps/cm^2, the average cell voltage will be $1.18 \times .85 = 1.0$ volts

TABLE A-4

TUBE PERFORMANCE AT 1423 K

Parameter	j=0.5 a/cm^2	0.4	0.3	0.2
$\Delta\dot{h}$ (cal/sec)	86.217	68.974	51.693	34.395
$\Delta\dot{g}$ (cal/sec)	53.038	42.430	31.800	21.220
i^2R (cal/sec)	8.575	5.488	3.087	1.372
$\dot{q}$ (cal/sec)	24.604	21.056	16.806	11.903
$\dot{m}$ (g-mol H_2O/sec)	1.3072-02	1.0458-02	0.7838-02	0.5209-02
δT (K)	177.0	192.0	207.0	223.0
$\frac{\Delta\dot{g} + i^2R^*}{\Delta\dot{g}}$	1.16	1.13	1.10	1.06

The production of hydrogen from the tubes is fixed by the current density for both cases, 1273 K and 1423 K, as follows:

$$\dot{m}(\text{g-mol } H_2/\text{sec}) = j \times 4.442 \text{ cm}^2/\text{cell} \times 125 \text{ cells} \times \frac{1\text{g-mol } H_2}{2 \times 96{,}500 \text{ amp sec}} .$$

The values of Table A-3 and Table A-4, calculated from $\dot{m}_{H_2} = 0.11\ \dot{m}_{H_2}$, check those from the coulomb transfer rate of Row 1.

The ratio of electric to thermal energy $\Delta\dot{g} + i^2R$: $\dot{q}$ for both cases follows:

	$j = 0.5$ a/cm^2	.4	.3	.2
Table A-3 (1273 K)	3.37	2.96	2.62	2.34
Table A-4 (1423 K)	2.50	2.28	2.08	1.99

Discussion

A HTE electrolyzer has been evaluated for performance parameters at two temperature levels, 1273 K and 1423 K. The thermal performance is not changed much at the two temperature levels. With a situation of slight temperature dependence, the need to perform a segment-by-segment calculation to account for temperature dependence is unnecessary. However, polarization effects, both slow and diffusive, have been neglected in the calculation.

The diffusive polarization can be neglected, especially if the porosity of the support tube is high, e.g., at 30% and any effect it may have would be greatest at 0.5 amp/cm^2.

Slow polarization is strongly temperature dependent, changing by a factor of ten times or so, between 900° and 1100°C, with present construction and electrode materials. It can be considered negligible at 1100°C; with near-term materials and construction, it is expected to control this to lower values at 900°C.

The calculated performance parameters indicate an acceptable electrolyzer performance. With near-term materials and construction techniques negating the above discussed polarization effects, one can expect this performance level to be obtainable in future HTE electrolyzer tubes.

APPENDIX B

A COMPUTER PROGRAM FOR ESTIMATING THE PERFORMANCE OF A HIGH-TEMPERATURE SOLID OXIDE ELECTROLYZER

R. E. Grimble

Introduction

A high-temperature solid oxide electrolyzer design for generating hydrogen from steam is described in Section 2. Performance calculations are described in Appendix A for several operating conditions. A computer program (LIZA) has been written to facilitate future performance calculations and to permit more extensive parametric studies.

Calculation Procedure

The analytical relationships and the method of calculation is similar in the computer program to that described in App. A, except that in the program:

1. Conditions are calculated explicitly for the axial section and numerically summed;
2. allowance is made for a difference in hydrogen partial pressure on the hydrogen electrode relative to the bulk stream as determined by a laminar flow mass transfer coefficient; and
3. allowance is made for oxygen partial pressure difference through the porous support tube due to viscous flow resistance.

The geometry is the same as shown in Fig. 2.1-2 but with arbitrary values of the individual physical dimensions. The input consists of:

1. The values of the physical dimensions,
2. the steam inlet temperature, pressure, and flow rate, and
3. the fraction of steam electrolyzed. This is discussed below in more detail.

The output includes:

1. Current required;
2. voltage required; and
3. temperature changes in the steam stream.

A program listing is included at the end of this section.

Data Input

In the notation used here, each axial segment is a cell. Input cards are prepared as follows.

Card 1 - Any alpha-numeric string in the first sixty columns to name or identify the case being considered.

Card 2 - Diameter measurements of cell components (in centimeters). These consist of six numerical values each in a ten-column interval according to an F 10.6 format:

A. Columns 1-10: support tube inner diameter, cm;

B. Columns 11-20: support tube outer diameter, cm;

C. Columns 21-30: oxygen electrode outer diameter, cm;

D. Columns 31-40: electrolyte outer diameter, cm;

E. Columns 41-50: hydrogen electrode outer diameter, cm; and

F. Columns 51-60: equivalent fuel passage diameter for estimating mass transfer coefficient, cm.

Card 3 - Two integers right justified in columns 1-10 and in columns 11-20; respectively. The first is the number of axial sections and the second indicates the frequency of printout (for example, the number 3 in column 20 results in numerical data printed out for every third axial section).

Card 4 - Length measurements of the cell and its components (in centimeters). These consist of five numerical values each in a ten-column interval according to an F 10.4 format.

A. Columns 1-10: the overall cell (axial segment) length, cm;

B. Columns 11-20: oxygen electrode length, cm; and

C. Columns 21-30: electrolyte length, cm.

(The overall assembly length is calculated from number of cells and cell length.)

Card 5, 6, 7, 8, and 9 - Each of these cards contains two numbers in scientific notation, using an E 10.4 format, which correlate component electricial resistivity (in ohm-cm) with temperature. A letter "A" in Columns 1-10 and a letter "B" in Columns 11-20 permit resistivity to be calculated from the formula

$$\rho = Ae^{(B/T)}$$

where T is absolute temperature in degrees Kelvin. These cards represent respectively:

1. the oxygen electrode;
2. the electrolyte;
3. the interconnect;
4. the hydrogen electrode; and
5. the electrode surface polarization resistivity (in ohm-cm^2).

Card 10 - In Columns 1-10, the support tube permeability in Darcys' and in Columns 11-20, the center-to-center tube spacing in a tube array in centimeters. These are entered according to a F 10.4 format.

Card 11 - In Columns 1-10, the steam absolute pressure in atmospheres; in Columns 11-20, the steam inlet temperature in degrees centigrade; in Columns 21-30, the steam flow rate per tube in g-moles/sec; and in Columns 31-40, the fraction of steam to be electrolyzed. These entries follow an F10.4 format.

Any number of eleven card data sets may be stacked together.

Output

A sample input deck and printout is shown at the end of this Section and is self-explanatory. First the input data are printed out. The current requirement (per tube) is printed out. Conditions at specified segments along the tube are printed out including the net voltage requirement and the overall temperature changes.

PROGRAM LISTING

```
12345678901234567890123456789012345678901234567890123456789012345678901234567890123456789012345678901234567890...SEQ.NO.01

@RL , /ANPT    LIZA,DREDDHTELOO1,GRIMALE,1,30

@ASG    FAULTIMODE.

@FOR,IS      LIZA
FOR   4R1    * -08/25/82-12:07:14 (,0)

   MAIN PROGRAM

   STORAGE USED: CODE(1) 001154; DATA(0) 013732; BLANK COMMON(2) 000000

   EXTERNAL REFERENCES (BLOCK, NAME)

    0003    EPG
    0004    TINTR$
    0005    NIOCB$
    0006    NWDFU$
    0007    KSCRT
    0010    NNRFU$
    0011    RPATH$
    0012    ALOCS
    0013    EPPS
    0014    RPARS
    0015    SORT$
    0016    NSTOP$
    0017    NRFCS

   STORAGE ASSIGNMENT  (BLOCK, TYPE, RELATIVE LOCATION, NAME)

    0000   013153 1F      0001   000033 100L    0000   013167 12F     0001   000467 126L    0001   000564 130L
    0001   001137 130L    0000   013202 14F     0001   001142 150L    0000   013213 16F     0000   013222 18F
    0000   013335 2F      0000   013230 20F     0000   013313 202D    0000   013320 204D    0000   013330 207D
    0000   013337 712D    0000   013346 215D    0000   013236 22F     0001   000052 220G    0000   013353 222D
    0000   013360 224G    0000   013366 232D    0000   013325 236D    0000   013246 24F     0000   013404 242D
    0001   000102 245G    0000   013411 247D    0000   013256 25F     0000   013416 251G    0000   013264 26F
    0001   000114 260G    0000   013424 267D    0000   013433 266D    0000   013440 270G    0000   013447 277D
    0000   013264 60F     0000   013137 3F      0000   013306 30F     0000   013536 303D    0000   013465 305G
    0000   013474 314D    0000   013306 32F     0000   013503 320D    0000   013511 323D    0000   013517 326D
    0000   013530 334D    0000   013536 337D    0000   013544 342D    0000   013552 345D    0000   013560 350D
    0001   000133 355G    0001   000267 372G    0000   013161 4F      0001   000360 410G    0000   013565 424D
    0000   013573 427D    0001   000426 433G    0001   000545 456G    0000   013600 460D    0000   013605 462G
    0000   013611 467D    0001   000562 473G    0001   001145 500L    0001   000602 503G    0001   000631 515G
    0000   013616 563D    0000   013162 6F      0000   013636 603D    0000   013164 8F      0000 R 013056 DLANK
    0000 R 013076 CENTER  0000 R 013136 COEFM  0000 R 013146 CPH     0000 R 013150 CPO     0000 R 013147 CPW
    0000 R 013115 CURNT   0000 R 013104 DAVE   0000 R 013152 DDELT   0000 R 013143 DELG    0000 R 013130 DELGO
    0000 R 013131 DELH    0000 R 013144 DELHG  0000 R 013121 DELP    0000 R 013105 DELA    0000 R 000156 DELT
    0000 R 013132 DENS    0000 R 013114 DFLOW  0000 R 000012 DIAM    0000 R 013135 DIFF    0000 R 013110 DON
    0000 R 013140 DP      0000 R 013106 DUP    0000 R 013133 DVOLM   0000 R 013111 EFLNG   0000 R 013063 ENCON
    0000 R 013061 FARDAY  0000 R 013101 FLOW   0000 R 013120 FLURH   0000 R 013116 FLUXO   0000 R 013102 FRACT
    0000 R 000144 GEOM    0000 R 002130 HEAT   0000 R 013113 HEATOT  0000 R 013151 HTCAP   0000 I 013071 I
    0000 I 013073 IPRINT  0000 I 013125 ITER   0000 I 013074 J       0000 I 013117 K       0000 I 000000 KASE
    0000 I 013055 L       0000 I 010020 LABL   0000 I 000024 LOCAT   0000 I 013057 LUNIT   0000 I 000062 MEMDFR
    0000 I 013070 MOLH    0000 I 013066 MOLO   0000 I 013067 MOLW    0000 I 013122 NSKIP   0000 I 013123 NSTAT
    0000 I 013124 NSTATI  0000 I 013072 NUMBER 0000 I 013103 NURBI   0000 R 013107 PEAM    0000 R 013075 PLAND
    0000 R 013141 PH      0000 R 013062 PI     0000 R 005064 PKH     0000 R 006050 PKW     0000 R 013137 PO
    0000 R 013077 PT      0000 R 013142 PW     0000 R 003114 QKH     0000 R 012064 QKO     0000 R 004100 QKW
    0000 R 000132 R       0000 R 013064 RCONA  0000 R 013065 RCOND   0000 R 000112 RESA    0000 R 000122 RESD
    0000 R 010134 RESHT   0000 R 010102 RESNC  0000 R 013127 RESTOT  0000 R 011100 RESVL   0000 R 010070 RESVT
    0000 R 000102 SPACE   0000 R 013060 TAR    0000 R 013126 TAVE    0000 R 013100 TIN     0000 R 007034 TK
    0000 R 013050 TP      0000 R 013143 TRANK  0000 R 013134 VISCOS  0000 R 000160 VHERN   0000 R 001144 VOLT
    0000 R 013112 VOLTAG

00101      1*          DIMENSION KASE(10),DIAM(10),LOCAT(10,3),MEMBER(8,2),SPACE(8)              000000
00103      2*          DIMENSION RESA(8),RESG(8),R(10),GEOM(10),DELT(2)                          000001
00104      3*          DIMENSION VHERN(500),VOLT(500),HEAT(500),QKH(500),QKW(500)                000001
00105      4*          DIMENSION PKH(500),PKW(500),TK(500),LABL(2,20),RESVT(10),RESNC(10)        000001
00106      5*          DIMENSION RESHT(500),RESVL(500),QKO(500),TP(5)                            000001
00107      6*        1 FORMAT('1')                                                               000001
00110      7*        2 FORMAT(6E10.4)                                                            000001
```

```
    3 FORMAT('0')
    4 FORMAT(10A6)
    6 FORMAT(7F10.4)
    8 FORMAT(2I10,5F10.3)
   12 FORMAT(3X,2A6,' RESISTIVITY=',F18.12,'*EXP(',F9.1,'/T) OHM-CM',A6)
   14 FORMAT('     SUPPORT TUBE PERMEABILITY=',F6.4,' DARCYS')
   16 FORMAT(3X,3A6,' DIAMETER=',F6.4,' CM.')
   18 FORMAT(5X,2A6,' LENGTH=', F7.3,' CM.')
   20 FORMAT('     PRESSURE=',F6.2,' ATM.')
   22 FORMAT('     INLET TEMPERATURE=',F8.2,' DEG.C')
   24 FORMAT('     STEAM FLOW RATE=', E10.4,' MOLE/SEC')
   25 FORMAT('     CURRENT=',F8.3,' AMPERES')
   26 FORMAT('     FRACTION OF STEAM ELECTROLYZED=',F6.4)
   28 FORMAT('     CENTER-TO-CENTER TUBE SPACING=',F6.4)
   30 FORMAT(12X,20A6)
   32 FORMAT('        SECTION ',I3,10F12.5)
      DATA  (LOCAT(3,L),L=1,3,1)  /'SUPPORT TUBE INNER'/
      DATA  (LOCAT(4,L),L=1,3,1)  /'SUPPORT TUBE OUTER'/
      DATA  (LOCAT(5,L),L=1,3,1)  /'O2 ELECTRODE OUTER'/
      DATA  (LOCAT(6,L),L=1,3,1)  /'ELECTROLYTE  OUTER'/
      DATA  (LOCAT(7,L),L=1,3,1)  /'H2 ELECTRODE OUTER'/
      DATA  (LOCAT(8,L),L=1,3,1)  /'EQUIV.FUEL PASSAGE'/
      DATA  (MEMBER(1,L),L=1,2,1) /'OVERALL CELL'/
      DATA  (MEMBER(2,L),L=1,2,1) /'O2 ELECTRODE'/
      DATA  (MEMBER(3,L),L=1,2,1) /'ELECTROLYTE '/
      DATA  (MEMBER(4,L),L=1,2,1) /'INTERCONNECT'/
      DATA  (MEMBER(5,L),L=1,2,1) /'H2 ELECTRODE'/
      DATA  (MEMBER(6,L),L=1,2,1) /'OVERALL TUBE'/
      DATA  (MEMBER(7,L),L=1,2,1) /'POLARIZATION'/
      DATA (LABL(1,L),L=1,20,1) /
     1 ' TEMPERATURE*H2 PARTIAL *NERNST POT.*I-R POTENT.*NET VOLTAGE',
     2 '*CUMULATIVE *DEL H-DEL G*RESISTANCE *NET HEAT   *CUMULATIVE '/
      DATA (LABL(2,L),L=1,20,1) /
     1 ' DEG. KELVIN*PRESS.,ATM *VOLTS      *DROP,VOLTS *VOLTS      ',
     2 '*VOLTAGE    *CAL/SEC    *HEAT,CAL/S.*CAL/SEC.   *HEAT,CAL/S.'/
      BLANK='      '
      LUNIT='-CM   '
      TAR=273.15
      FARDAY=96501.0
      PI=3.14156
      ENCON=0.239006
C**     CAL/WATT-SEC
      RCONA=82.003
C**     ATM-CM3/MOLE-DEG.K
      RCONB=1.9872
C**     CAL/MOLE-DEG.K
      MOLO=31.9988
      MOLW=18.0153
      MOLH= 2.0159
      WRITE(6,1)
  100 READ(5,4,END=500) (KASE(I),I=1,10,1)
      READ(5,6) (DIAM(I),I=3,8,1)
      WRITE(6,4)(KASE(I),I=1,10,1)
      WRITE(6,3)
      DO 106 I=3,7,1
  106 WRITE(6,16) (LOCAT(I,L),L=1,3,1),DIAM(I)
      READ(5,8) NUMBER,IPRINT
      READ(5,6) (SPACE(J),J=1,5,1)
      SPACE(8)=NUMBER*SPACE(1)
      WRITE(6,3)
      DO 108 J=1,4,1
  108 WRITE(6,18)(MEMBER(J,L),L=1,2,1),SPACE(J)
      DO 110 J=2,5,1
      READ(5,2)   RESA(J),RESB(J)
  110 WRITE(6,12) (MEMBER(J,L),L=1,2,1),RESA(J),RESB(J)
      READ(5,2)   RESA(7),RESB(7)
      WRITE(6,12) (MEMBER(7,L),L=1,2,1),RESA(7),RESB(7),LUNIT
      READ(5,6)   PERMD,CENTER
      WRITE(6,14) PERMD
      WRITE(6,28) CENTER
      READ(5,6)   PT,TIN,FLOW,FRACT
      WRITE(6,20) PT
      WRITE(6,22) TIN
      WRITE(6,24) FLOW
      WRITE(6,26) FRACT
      WRITE(6,3)
```

```
      RESA(6)=0.0
      RESB(6)=0.0
      DC 116 I=3,8,1
  116 R(I)=DIAM(I)/2.0
      NUMB1=NUMBER+1
      DAVE=R(5)+R(4)
      DELR=R(5)-R(4)
      DUP=DAVE+DELR/2.0
      PERM=PERMD/100.0
C** TO ALLOW FOR VISCOSITY IN POISE INSTEAD OF C.P.
      GEOM(2)= 0.5*SPACE(2)/(PI*DAVE*DELR)+(0.5*DELR/(PI*DUP))
     1        *(1.0/SPACE(3)+1.0/SPACE(4))
      DAVE=R(6)+R(5)
      DELR=R(6)-R(5)
      DO 120 I=3,4,1
  120 GEOM(I)=DELR (PI*DAVE*SPACE(I))
      DAVE=R(6)+R(7)
      DELR=R(7)-R(6)
      DON=DAVE-DELR/2.0
      GEOM(5)=0.5*SPACE(5)/(PI*DAVE*DELR)+(0.5*DELR/(PI*DON))
     1        *(1.0/SPACE(3)+1.0/SPACE(4))
      GEOM(1)=(SPACE(3)+(R(4)-R(3))/2.0)*PI*DIAM(3)
      EFLNG=SPACE(3)+(R(4)-R(3))/4.0
      GEOM(6)=(SPACE(3)+(R(7)-R(6))/2.0)*PI*R(7)*2.0
      GEOM(7)=1.0/((SPACE(3)+(R(7)-R(6))/4.0)*PI*(R(7)+R(6)))
      GEOM(8)=(SPACE(3)+(R(7)-R(6))/2.0)*PI*DIAM(7)
      DO 122 I=1,7,6
  122 IF(GEOM(I).C!.SPACE(1)) GEOM(I)=SPACE(1)
      VOLTAG=0.0
      HEATOT=0.0
      TK(1)=TIN+TAB
      PKH(1)=PT
      PKW(1)=0.0
      DFLOW=FLOW*FRACT/NUMBER
      CURNT=DFLOW*2.0*FARDAY
      WRITE(6,25) CURNT
      WRITE(6,5)
      FLUXO=DFLOW/(2.0*GEOM(1))
      DO 124 K=1,NUMB1,1
      QKW(K)=FLOW-DFLOW*(K-1)
      QKH(K)= DFLOW*(K-1)
      QKO(K)= DFLOW*(K-1)/2.0
      PKH(K)=PT*QKH(K)/FLOW
  124 PKW(K)=PT*QKW(K)/FLOW
      FLUXH=DFLOW/GEOM(8)
      DELP=FRACT*PT/NUMBER
      NSKIP=0
  126 NSKIP=NSKIP+1
      NSTAT=(NUMBER/NSKIP)
      IF(NSTAT.GT.10) GO TO 126
      NSTAT1=NSTAT
      IF((NSTAT*NSKIP).GT.NUMBER) NSTAT1=NSTAT+1
      DO 128 J=1,2,1
  128 WRITE(6,30) (LABL(J,K),K=1,20,1)
      WRITE(6,5)
      DELT(2)=0.0
      DO 150 K=1,NUMBER,1
      ITER=0
  130 ITER=ITER+1
      DELT(1)=DELT(2)
      TAVE=TK(K)+DELT(1)/2.0
      RESTOT=0.0
      DO 132 I=2,7,1
      RESVT(I)=RESA(I)*EXP(RESB(I)/TAVE)
      RESNC(I)=RESVT(I)*GEOM(I)
  132 RESTOT=RESTOT+RESNC(I)
      RESVL(K)=CURNT*RESTOT
      RESHT(K)=CURNT*RESVL(K)*ENCON
      TP(1)=TAVE
      DO 134 I=2,3,1
  134 TP(I)=TAVE*TP(I-1)
      DELGO=-57410.0+0.94*TP(1)*ALOG(TP(1))+(1.65E-03)*TP(2)
     1      -(3.7E-07)*TP(3)+3.92*TP(1)
      DELH =-57410.0-0.94*TP(1)           -(1.65E-03)*TP(2)
     1      +(7.4E-07)*TP(3)
      DENS =PT/(RCONA*TAVE)
```

```
00524          DVOLM=DFLOW/DENS                                                  C00673
00525          CALL EMU(TAVE,PT,VISCOS)                                          C00676
00526          TP(1)=TAVE                                                        C00702
00527          DIFF= 0.734*((TAVE/273.)**1.82)/PT                                000705
00530          COEFM=0.75*DIFF/R(8)                                              000715
00550    C** JAKOB P. 467                                                        C00715
00551          PO=PT-ALOG(R(4)/R(3))*VISCOS*DFLOW/(4.0*PI*PERM*DENS*EFLNG)       000720
00532          DP=FLUXH*RCONA*TAVE/COEFM                                         C00731
00533          PH=(PKH(K)+PKH(K+1))/2.0+DP                                       000735
00534          PW=(PKW(K)+PKW(K+1))/2.0-DP                                       C00742
00535          DELG =DELGO+RCONA*TAVE*ALOG(PW/(PH*SQRT(PO)))                     000747
00536          VNERN(K)=-DELG/(2.0*FARDAY*ENCON)                                 C00765
00537          VOLT(K)=VNERN(K)+RESVL(K)                                         030767
00540          DELHG=(DELH-DELG)*DFLOW                                           C00771
00541          HEAT(K)=(DELH-DELG)*DFLOW+RESHT(K)                                000773
00542          TRANK=TAVE*1.8                                                    001002
00543          CPH=5.76+(0.578*TRANK/1000.0) +20.0/SQRT(TRANK)                   001005
00544          CPW=19.86-(597.0/SQRT(TRANK))+ 7500.0/TRANK                       001017
00545          CPO=11.515-172.0/SQRT(TRANK)+1530.0/TRANK                         001032
00546          HTCAP= ((QKO(K)+QKO(K+1))*CPO+(QKH(K)+QKH(K+1))*CPH               001045
00546         1        + (QKW(K)+QKW(K+1))*CPW)/2.0                              001045
00547          DELT(2)= HEAT(K)/HTCAP                                            C01062
00550          DDELT=DELT(2)-DELT(1)                                             C01065
00551          IF(ABS(DDELT).GT.0.01.AND.ITER.LT.10) GO TO 130                   001067
00553          VCLTAG=VOLTAG+VOLT(K)                                             001105
00554          HEATOT=HEATOT+HEAT(K)                                             001110
00555          TK(K+1)=TK(K)+DELT(2)                                             001113
00556          IF(K.EQ.NUMB1) GO TO 138                                          C01116
00560          IF((FLOAT(K-1)/FLOAT(IPRINT)).EQ.FLOAT((K-1)/IPRINT)) GO TO 138   C01121
00562          GC TO 150                                                         C01135
00563      138 WRITE(6,32) K,TK(K),PKH(K),VNERN(K),RESVL(K),VOLT(K),VOLTAG,      001137
00563         1       DELHG,RESHT(K),HEAT(K),HEATOT                              001137
00600      150 CCNTINUE                                                          001143
00602          GC TO 100                                                         001143
00603      500 WRITE(6,3)                                                        C01145
00605          STOP                                                              001145
00606          END                                                               001153

     END OF COMPILATION:          NO  DIAGNOSTICS.

@FOR,IS      EMU
FOR   4R1    T -08/25/82-12:07:22 (,0)

   SUBROUTINE EMU         ENTRY POINT 000127

   STORAGE USED: CODE(1) 000147; DATA(0) 000146; BLANK COMMON(2) 000000

   STORAGE ASSIGNMENT  (BLOCK, TYPE, RELATIVE LOCATION, NAME)

    0001   000006 125G      0001   000036 135G      0001   000056 144G      0000   000127 DYNS      0000 I 000117 I
    0000 I 000121 IT        0000 I 000122 IT1       0000 I 000124 J         0000 I 000126 JJ        0000 I 000123 JP
    0000 I 000125 JP1       0000 R 000110 P         0000 R 000074 T         0000 R 000000 VIS       0000 R 000115 VISA
    0000 R 000120 VISCON


00101          SUBROUTINE EMU(TEMP,PRES,VISC)                                    000000
00103          DIMENSION VIS(12,5),T(12),P(5),VISA(2)                            000000
00104          DATA (VIS(I,1),I=1,12,1)       / 147.5,207.2,258.2,               000000
00104         1     303.3,343.7,380.8,415.2,447.2,477.0,505.5,532.5,558.4 /      000000
00106          DATA (VIS(I,2),I=1,12,1)       / 153.2,210.7,260.7,               000000
00106         1     305.3,345.3,382.2,416.4,448.3,477.9,506.3,533.3,559.1 /      000000
00110          DATA (VIS(I,3),I=1,12,1)       / 158.1,213.5,262.8,               000000
00110         1     307.0,346.8,383.4,417.5,449.2,478.8,507.2,534.1,559.8 /      000000
00112          DATA (VIS(I,4),I=1,12,1)       / 173.7,219.8,266.8,               000000
00112         1     309.8,349.0,385.2,419.0,450.6,480.0,508.2,535.1,560.7 /      000000
00114          DATA (VIS(I,5),I=1,12,1)       / 190.3,225.4,270.2,               000000
00114         1     312.4,351.0,386.9,420.4,451.8,481.1,509.2,535.9,561.5 /      000000
00116          DATA T /      200.0,300.0,400.0,                                  000000
00116         1     500.0,600.0,700.0,800.0,900.0,1000.,1100.,1200.,1300.0/      000000
```

```
00120              DATA P /    1.0 , 20.0, 40.0, 60.0, 80.0 /                                000000
00122              VISCON=10.0                                                               000000
00123              IT=1                                                                      000001
00124              DO 12 I=2,11,1                                                            000006
00127           12 IF(TEMP.GT.T(I)) IT=I                                                     000006
00132              IT1=IT+1                                                                  000016
00133              JP=1                                                                      000027
00134              DO 14 J=2,4,1                                                             000036
00137           14 IF(PRES.GT.P(J)) JP=J                                                     000036
00142              JP1=JP+1                                                                  000046
00143              DO 16 J=1,2,1                                                             000051
00146              JJ=JP+J-1                                                                 000056
00147           16 VISA(J)= VIS(IT,JJ)+(VIS(IT1,JJ)-VIS(IT,JJ))*(TEMP-T(IT))                 000067
00147            )          /(T(IT1)-T(IT))                                                  000067
00151              VISC =VISA(1)+(VISA(2)-VISA(1))*(PRES-P(JP))/(P(JP1)-P(JP))               000077
00152              VISC=VISC*VISCON/(1.0E07)                                                 000111
00153              RETURN                                                                    000114
00154              END                                                                       000146

      END OF COMPILATION:        NO  DIAGNOSTICS.

@MAP,SIKE
MAP 30R1E2 S74T11 08/25/82 12:07:24
    1.            LIB LIBRARY*FORTRAN

APCM STATUS OF OUTPUT ELEMENT=UNKNOWN
QUARTER/THIRD WORD INSENSITIVE

ADDRESS LIMITS     001000 003332       1243 IBANK WORDS DECIMAL
                   040000 062234       9373 DBANK WORDS DECIMAL
STARTING ADDRESS   002157


            SEGMENT $MAIN$          001000 003332      040000 062234

CBEP$$CML                                                                     19 FEB 81    10:55:57
SYSTIM                                               $(0)    040000 040341    24 FEB 75    09:03:00
ERU$/SYS74R1W1                                                                14 JAN 80    10:42:14
CBEPFORV$/SYS73                                                               24 SEP 76    21:28:10
CERU$/SYS74R1W5                                                               03 AUG 82    11:28:25
INTROS$/WRL-F                  $(1)    001000 001602    $(0)    040342 040575    29 NOV 79    13:08:05
                               $(3)    BLANK$COMMON     $(2)    040576 042274
                               $(5)    NS0S0S           $(4)    MOEROS
                                                        $(6)    INFO-010-LC
NRECA$/FOR-T3                                           $(2)    042275 042407    11 MAR 75    15:28:20
CLOSE$/FOR4R1-T                $(1)    001603 001627    $(2)    042410 042413    27 JUL 78    16:57:15
                               $(057)  INFO-010-LC
NTAB$/WRL                                               $(2)    042414 042451    14 AUG 74    10:52:09
FORCOM$/FORFTN                                          $(2)    042452 042457    31 AUG 78    14:44:53
MOEROS(COMMONBLOCK)                                             042460 042463
TINTAS$Q/T4-WRL-F              $(3)    MOEROS           $(2)    042464 043542    03 JAN 80    16:24:17
TINTR$/T4-WRL                  $(1)    001630 001635    $(0)    043543 043553    15 MAY 79    10:33:25
NSCR$/FOR-T3                                            $(2)    043554 043717    11 MAR 75    15:28:34
                                                        $(4)    NS0S0S
NS0S0S(COMMONBLOCK)                                             043720 043722
NBF0$-T                                                 $(2)    043723 046024    11 MAR 75    15:21:51
                                                        $(4)    NS0S0S
NERCOM$/FOR-7E3                $(1)    001636 001715    $(2)    046025 046040    11 MAR 75    15:33:59
FORVCOM$/FOR4R1                                         $(2)    046041 046050    28 JUL 78    14:56:41
NSTOP$/T4-WRL-F                $(1)    001716 002007    $(2)    046051 046134    04 JAN 80    13:59:24
BLANK$COMMON(COMMONBLOCK)
EMU                            $(1)    002010 002156    $(0)    046135 046302    25 AUG 82    12:07:24
                               $(3)    INFO-010-LC      $(2)    BLANK$COMMON
LIZA                           $(1)    002157 003332    $(0)    046303 062234    25 AUG 82    12:07:22
                               $(3)    INFO-010-LC      $(2)    BLANK$COMMON

COMMON BANKS REFERENCED

  0400001  0400004  0400006
SYS$*RLIB$. LEVEL 74R1
```

SAMPLE INPUT DECK

ELECTROLYZER PERFORMANCE

1.0700	1.2700	1.4100	1.4180	1.4380	.9955
125	2				
1.2500	1.2500	1.0000	.2500	1.2500	
.8114-02	.6000+03				
.2948-02	.1035+05				
.1256+00	.4690+04				
.2980-02	-.1392+04				
.0000	.0000				
2.0000	1.5500				
34.0000	1000.0000	.0124	.1100		

SAMPLE OUTPUT

ELECTROLYZER PERFORMANCE

```
SUPPORT TUBE INNER DIAMETER=1.0700 CM.
SUPPORT TUBE OUTER DIAMETER=1.2700 CM.
O2 ELECTRODE OUTER DIAMETER=1.4100 CM.
ELECTROLTE   OUTER DIAMETER=1.4180 CM.
H2 ELECTRODE OUTER DIAMETER=1.4380 CM.

OVERALL CELL LENGTH=  1.250 CM.
O2 ELECTRODE LENGTH=  1.250 CM.
ELECTROLYTE  LENGTH=  1.000 CM.
INTERCONNECT LENGTH=   .250 CM.
H2 ELECTRODE LENGTH=  1.250 CM.
OVERALL TUBE LENGTH=156.250 CM.
O2 ELECTRODE RESISTIVITY=       .00811399967*EXP(   600.0/T) OHM-CM
ELECTROLYTE  RESISTIVITY=       .00294800008*EXP( 10350.0/T) OHM-CM
INTERCONNECT RESISTIVITY=       .12560000843*EXP(  4690.0/T) OHM-CM
H2 ELECTRODE RESISTIVITY=       .00297999990*EXP( -1392.0/T) OHM-CM
POLARIZATION RESISTIVITY=       .00000000000*EXP(      .0/T) OHM-CM-CM
SUPPORT TUBE PERMEABILITY=2.0000DARCYS
CENTER-TO-CENTER TUBE SPACING=1.5500
PRESSURE= 34.00 ATM.
INLET TEMPERATURE= 1000.00 DEG.C
STEAM FLOW RATE=  .1242-01 MOLE/SEC
FRACTION OF STEAM ELECTROLYZED= .1100

CURRENT=   2.109 AMPERES
```

		TEMPERATURE DEG. KELVIN	H2 PARTIAL PRESS.,ATM	NERNST POT. VOLTS	I-R POTENT. DROP,VOLTS	NET VOLTAGE VOLTS	CUMULATIVE VOLTAGE	DEL H-DEL G CAL/SEC	RESISTANCE HEAT,CAL/S.	NET HEAT CAL/SEC.	CUMULATIVE HEAT,CAL/S.
SECTION	1	1273.14999	.00000	.77403	.14577	.91979	.91979	-.26284	.07349	-.18935	-.18935
SECTION	3	1270.30609	.05984	.78175	.14642	.92817	2.77204	-.25690	.07382	-.18508	-.56159
SECTION	5	1267.52402	.11968	.78873	.14707	.93580	4.63991	-.25333	.07415	-.18118	-.92585
SECTION	7	1264.79851	.17952	.79512	.14772	.94285	6.52219	-.25006	.07448	-.17759	-1.28579
SECTION	9	1262.12524	.23936	.80100	.14837	.94937	8.41767	-.24905	.07480	-.17425	-1.63293
SECTION	11	1259.50067	.29920	.80647	.14902	.95549	10.32565	-.24625	.07513	-.17112	-1.97670
SECTION	13	1256.92175	.35904	.81158	.14967	.96125	12.24531	-.24363	.07546	-.16817	-2.31449
SECTION	15	1254.38509	.41888	.81638	.15032	.96670	14.17602	-.24116	.07578	-.16538	-2.64663
SECTION	17	1251.89087	.47872	.82092	.15097	.97188	16.11723	-.23884	.07611	-.16272	-2.97338
SECTION	19	1249.43469	.53856	.82520	.15162	.97682	18.06843	-.23663	.07644	-.16019	-3.29502
SECTION	21	1247.01564	.59840	.82928	.15227	.98154	20.02918	-.23453	.07677	-.15777	-3.61175
SECTION	23	1244.63214	.65824	.83316	.15292	.98608	21.99909	-.23255	.07710	-.15544	-3.92378
SECTION	25	1242.28284	.71808	.83687	.15357	.99044	23.97782	-.23062	.07743	-.15320	-4.23128
SECTION	27	1239.96646	.77792	.84043	.15422	.99465	25.96503	-.22879	.07776	-.15103	-4.53442
SECTION	29	1237.68190	.83776	.84384	.15488	.99872	27.96045	-.22703	.07809	-.14894	-4.83335
SECTION	31	1235.42812	.89760	.84712	.15554	1.00265	29.96380	-.22534	.07842	-.14692	-5.12817
SECTION	33	1233.20616	.95744	.85028	.15619	1.00647	31.97485	-.22370	.07875	-.14495	-5.41907
SECTION	35	1231.00919	1.01728	.85333	.15685	1.01018	33.99337	-.22213	.07908	-.14305	-5.70617
SECTION	37	1228.84238	1.07712	.85627	.15752	1.01379	36.01916	-.22060	.07941	-.14119	-5.98941
SECTION	39	1226.70500	1.13696	.85912	.15818	1.01730	38.05201	-.21913	.07975	-.13938	-6.26907
SECTION	41	1224.59058	1.19680	.86188	.15884	1.02073	40.09176	-.21770	.08008	-.13761	-6.54518
SECTION	43	1222.50385	1.25664	.86456	.15951	1.02407	42.13824	-.21631	.08042	-.13589	-6.81782
SECTION	45	1220.44283	1.31648	.86716	.16017	1.02734	44.19129	-.21496	.08076	-.13421	-7.08706
SECTION	47	1218.40677	1.37632	.86969	.16084	1.03053	46.25077	-.21365	.08109	-.13256	-7.35300
SECTION	49	1216.39514	1.43616	.87215	.16151	1.03366	48.31653	-.21237	.08143	-.13094	-7.61569
SECTION	51	1214.40746	1.49600	.87454	.16219	1.03673	50.38846	-.21113	.08177	-.12936	-7.87520
SECTION	53	1212.44324	1.55584	.87687	.16286	1.03973	52.46643	-.20992	.08211	-.12781	-8.13160
SECTION	55	1210.50200	1.61568	.87914	.16353	1.04268	54.55032	-.20874	.08245	-.12628	-8.38495
SECTION	57	1208.58353	1.67552	.88136	.16421	1.04557	56.64002	-.20759	.08279	-.12480	-8.63527
SECTION	59	1206.68721	1.73536	.88353	.16489	1.04842	58.73544	-.20646	.08313	-.12333	-8.88266
SECTION	61	1204.81674	1.79520	.88564	.16557	1.05121	60.83647	-.20536	.08347	-.12188	-9.12715
SECTION	63	[illegible]202.95979	1.85504	.88771	.16625	1.05396	62.94302	-.20428	.08382	-.12046	-9.36878
SECTION	65	1201.12601	1.91488	.88973	.16693	1.05666	65.05499	-.20323	.08416	-.11907	-9.60761
SECTION	67	1199.31705	1.97472	.89171	.16762	1.05932	67.17232	-.20220	.08451	-.11769	-9.84368
SECTION	69	1197.52664	2.03456	.89365	.16830	1.06195	69.29490	-.20119	.08485	-.11634	-10.07703
SECTION	71	1195.75647	2.09440	.89554	.16899	1.06453	71.42267	-.20020	.08520	-.11500	-10.30770
SECTION	73	1194.00626	2.15424	.89740	.16967	1.06708	73.55555	-.19923	.08554	-.11368	-10.53572
SECTION	7[illegible]	[illegible].27573	2.21408	.89922	.17036	1.06959	75.69347	-.19828	.08589	-.11239	-10.76114
SECTION	7[illegible]	[illegible].56464	2.27392	.90101	.17105	1.07206	77.83636	-.19734	.08624	-.11111	-10.98399

SECTION 79	1188.87271	2.33376	.90276	.17174	1.07451	79.98415	-.19643	.08659	-.10984	-11.20431
SECTION 81	1187.19974	2.39360	.90449	.17243	1.07692	82.13679	-.19553	.08695	-.10860	-11.42212
SECTION 83	1185.54549	2.45144	.90617	.17312	1.07930	84.29420	-.19465	.08728	-.10736	-11.63746
SECTION 85	1183.90967	2.51128	.90783	.17382	1.08165	86.45632	-.19378	.08763	-.10615	-11.85038
SECTION 87	1182.29214	2.57312	.90946	.17451	1.08397	88.62311	-.19293	.08798	-.10495	-12.06085
SECTION 89	1180.69266	2.63296	.91106	.17520	1.08627	90.79450	-.19209	.08833	-.10376	-12.26896
SECTION 91	1179.11104	2.69280	.91264	.17590	1.08854	92.97044	-.19127	.08868	-.10258	-12.47471
SECTION 93	1177.54707	2.75264	.91418	.17660	1.09078	95.15088	-.19046	.08903	-.10142	-12.67813
SECTION 95	1176.00056	2.81248	.91571	.17729	1.09300	97.33577	-.18966	.08938	-.10028	-12.87925
SECTION 97	1174.47134	2.87232	.91720	.17799	1.09519	99.52506	-.18888	.08974	-.09914	-13.07810
SECTION 99	1172.95921	2.93216	.91868	.17868	1.09736	101.71870	-.18810	.09009	-.09802	-13.27470
SECTION 101	1171.46400	2.99200	.92013	.17938	1.09951	103.91664	[illegible]	.09044	-.09691	-13.46906
SECTION 103	1169.98557	3.05184	.92155	.18008	1.10163	106.11885	-.18660	.09079	-.09581	-13.66123
SECTION 105	1168.52371	3.11168	.92296	.18078	1.10373	108.32526	-.18586	.09114	-.09472	-13.85121
SECTION 107	1167.07828	3.17152	.92434	.18147	1.10581	110.53585	-.18514	.09149	-.09364	-14.03903
SECTION 109	1165.64912	3.23136	.92570	.18217	1.10787	112.75058	-.18442	.09184	-.09258	-14.22471
SECTION 111	1164.23608	3.29120	.92705	.18287	1.10991	114.96939	-.18372	.09220	-.09152	-14.40828
SECTION 113	1162.83899	3.35104	.92837	.18356	1.11193	117.19224	-.18302	.09255	-.09048	-14.58975
SECTION 115	1161.45772	3.41088	.92967	.18426	1.11393	119.41911	-.18234	.09290	-.08944	-14.76915
SECTION 117	1160.09212	3.47072	.93096	.18496	1.11592	121.64996	-.18166	.09325	-.08841	-14.94649
SECTION 119	1158.74203	3.53056	.93223	.18565	1.11788	123.88473	-.18100	.09360	-.08740	-15.12179
SECTION 121	1157.40736	3.59040	.93348	.18635	1.11982	126.12341	-.18034	.09395	-.08639	-15.29508
SECTION 123	1156.08792	3.65024	.93471	.18704	1.12175	128.36594	-.17970	.09430	-.08540	-15.46637
SECTION 125	1154.78362	3.71008	.93592	.18773	1.12366	130.61231	-.17906	.09465	-.08441	-15.63568

@FIN

APPENDIX C

BASIS FOR THE SIZING AND COSTING OF HYFIRE COMPONENTS

The basis for the size and the cost estimates for the various components in Cost Accounts 22 (Reactor Plant Equipment) and 23 (Turbine Plant Equipment) are discussed in this Section. The designs of the components and their sizing are based on the HYFIRE flow sheets shown in Section 3 and the state points (fluid stream temperatures, pressures, flow rates, and the amount of heat transferred). The major component items in these accounts, the number of units of each type of component, and the component design parameters are summarized together with the cost coefficients, scale factors, and the total component hardware cost (one or more units) in Table 5.2-1. The bulk of the estimated bare equipment costs are obtained from algorithms developed from various published costs for processing and heat transport apparatus. These algorithms involve fractional power scaling for the main cost determinators (e.g., ft^2 heat transfer surface, brake horsepower, and design pressure, where applicable). The cost coefficients and the scale factors are given based on the following generalized costing algorithm:

$$\text{Cost/Unit} = \$C_o \gamma_o \, (A)^{\alpha_1} \, (P)^{\alpha_2} \, (B)^{\alpha_3} \, (W)^{\alpha_4} \, (M)^{\alpha_5} \, (Q)^{\alpha_6}$$

where C_o is the cost coefficient, γ_o is a multiplicative factor; α_1, α_2, α_3, α_4, α_5, and α_6 are scale factors; A is the external heat transfer surface area in ft^2; P is the design pressure in psia; B is the brake horsepower; W is the flow rate in gpm; M is the mass in pounds; and Q is the turbine output in MW. The generalized costing algorithm is applicable to all the major components in the cost accounts as determined by the scale factors. Thus for heat exchangers, α_3, α_4, α_5, and α_6 are zeros and the costing algorithm reduces to:

$$\text{Cost/Unit} = \$C_o Y_o (A)^{\alpha_1} (P)^{\alpha_2} .$$

The specific functions of the major components and general descriptions of the components are discussed in the following sections.

Account 22 - Reactor Plant Equipment

22.02.01 Primary to Secondary Helium Heat Exchangers

This consists of a parallel set of 420 heat exchanger modules that transfer heat from the primary helium to the secondary helium. Each module is a countercurrent flow, floating head design with one tube pass. The tubes and shell are made of Inconel. Each module contains 1297 tubes 0.25 inch o.d. and 0.022 wall thickness with 0.375 inch triangular pitch array. The shell is 15.25 inch o.d. and 0.375 inch thick.

22.02.02 Primary Helium Circulating Compressors

These compressors provide the circulation of the primary helium coolant that transports the heat generated in the tritium breeding blankets to the primary helium-to-helium heat exchanger. Twenty-eight single stage centrifugal compressors were selected. The brake horsepower per unit is 9000 HP and the overall dimensions per unit are 8.3 x 9.9 feet. Costing was based on a design pressure of 720 psia and helium flow rate of 1.33×10^7 lb/hr.

22.02.03 Secondary Helium Circulating Compressors

The secondary helium circulating compressors move the secondary helium through the helium-to-helium primary heat exchanger and transports the heat to the boiler-superheater. Twenty-eight single stage centrifugal compressors were again selected. The brake horsepower is 3700 HP per unit.

22.02.04 Oxygen Regenerative Coolers

Eight coolers, operating in parallel, were selected. Each unit was designed with countercurrent flow, fixed heat, one tube pass, SS-316, and with oxygen flowing through the tubes. There are 3955 tubes per unit. The tubes are 0.375 inch o.d., 0.049 inch wall thickness and 118 inches long.

22.02.05 Boiler Superheaters

A parallel set of twelve boiler-superheaters generate the steam for the high-pressure turbine. The boiler-superheaters consist of countercurrent flow, floating head, one tube pass, and high nickel heat exchangers. The cold fluid flows through the tubes. The tubes are 1 inch o.d. with a 0.109 inch wall thickness. There are 7610 tubes per unit. The hell is 139 inch o.d. and 0.6 inch thick and has a length of 387 inches.

22.02.06 Pressurized Water Circulating Pumps

These pumps circulate pressurized water through the first wall. The pumps are of the single stage, centrifugal type--each one delivers 12,000 gpm. The design pressure is 4300 psia. The brake horsepower is 510 HP per unit. Thirteen operating units are required. Two installed spares are provided.

Account 23--Turbine Plant Equipment

23.01 Turbine Generators

The sizing and costing of the power generating turbines were scaled from STARFIRE. A scale factor of 0.6, based on the turbine output, was assumed. The three different turbines involved are the high-pressure turbine, low-pressure turbine, and the oxygen turbine. The high-pressure turbine produces 524 MW of electricity (by assuming 36% overall turbine efficiency). The low-pressure turbine produces 1628 MW, while the oxygen turbine produces 57 MW.

23.03 Plant Cooling Water Heat Dump System

Two heat dump systems are required--one that provides 80°F cooling water and the other provides 90°F cooling water. Both systems provide 70 psia cooling water in closed loops with cooling of returned heating water to hyperbolic evaporative cooling towers. The 80°F system consists of three 2.17×10^4 gpm cooling towers and six 2.7×10^3 BHP pumps (3.6×10^4 gpm water circulating capacity). The 90°F system consists of one 2.73×10^5 gpm cooling tower and two 2.4×10^3 BHP (1.37×10^5 gpm) circulating pumps. Both systems provide 43% excess cooling capacity.

23.04.01 Main Condensers

The saturated H_2-H_2O vapor exhausting from the low-pressure turbine is condensed in sixteen condensers using the plant cooling water. The design is similar to the feed preheaters (23.05.05) with the exception of the tube length (661 inch), number of tubes (19,400), the shell (122 inch i.d. and 1.5 inch wall thickness), and the overall dimensions (10.42 feet o.d. x 61.08 feet long).

23.04.02 H_2-H_2O Vapor After-Cooler of the Main Condensers

One after-cooler processes the H_2-H_2O vapor generated by the sixteen main condensers. The saturated H_2-H_2O vapor withdrawn from the main condensers are cooled further by the plant cooling water in this heat exchanger. The heat exchanger is similar to the feed preheaters (23.05.05) with the exception of the tube length (114 inch), number of tubes (2425), shell size (44 inch i.d. with 0.25 inch wall thickness), and the external heat transfer surface area (3770 ft^2).

23.05.01 Oxygen After-Cooler, Cooling Water Circulating Pumps

Two multistage centifugal pumps with 700 gpm capacities are required. Each unit has design pressure of 1130 psia and brake power of 890 HP.

23.05.02 Circulating Pumps for Water Feed to Feed Preheater

Three multistage centrifugal pumps of 12,000 gpm capacity are required. The design pressure is 1130 psia and the brake horsepower is 12,650 HP.

23.05.03 Circulating Pumps for Water Feed to Boiler-Superheaters

Same specs as those given in 23.05.02 except design pressure of 1900 psia. Four units are required, and two spares are provided.

23.05.04 Circulating Pumps for Make-up and Recycle Water

Three pumps of single stage centrifugal design are designed for 12000 gpm capacity and 60 psia pressure. Two spares are provided.

23.05.05 Feed Preheaters

The cold boiler feedwater is heated by superheated steam extracted from the high-pressure turbine. The condensate generated is mixed with other streams to form feed for the boiler-superheaters. The feed preheaters consist of four parallel operated, single tube pass designs with countercurrent flow (with the cold fluid flowing through the tubes.) High nickel content tubes are specified. Each unit has 14,870 tubes that have 0.625 inch o.d., 0.035 inch wall thickness and 741 inch length. The total length accommodates a 213 inch long desuperheating zone, 284 inch condensing zone and 244 inch condensate sub-cooling zone. The shell has 108 inch i.d. and 1.5 inch wall thickness. The external heat transfer surface per unit is 150,230 ft^2.

23.05.06 Desuperheater - Condensers for Degassing Heater

Cold boiler feedwater is heated by superheated steam extracted from the low-pressure turbine. The condensate generated is mixed with other streams to form feed for the boiler-superheaters. The heat exchanger is accomplished in four parallel-operated second stage pressurized water preheaters. The heater tubes are identical to those of the feed preheaters with the exception of the length. The 14,870 486-inch long tubes have 149-inch long desuperheating zones and 337-inch condensing zones. The shell is 108 inch i.d. with a 1-inch wall thickness.

23.05.07 H_2-H_2O Vapor After-cooler of the Degassing Heaters

Boiler feed water is heated by the hot H_2-H_2O vapor generated by the set of four degasser-heater units which, subsequent to cooling, is dispatched to the third stage of the H_2 product compressor-after-cooler complex. This is accomplished in a single heat exchanger with the same basic features as the desuperheater-condensers described above. The 817 tubes are 191 inch long. The shell is 46 inch in i.d. with a wall thickness of 0.75 inch.

23.05.08 Desuperheater Condenser for Feed-water Heater

Cold boiler feed water is heated in these heat exchangers (7 units) by the hot superheated steam extracted from the low-pressure turbine. The condensate generated is mixed with other streams to form the feed for the boiler-superheaters. These heat exchangers are identical to the desuperheater-condensers for the degassing heater described previously. The only differences are the length of the tubes--658 inch, the overall length of each unit (60.83 feet) and the external heat transfer area—133,400 ft^2.

23.05.090 H_2-H_2O Vapor After-cooler of the Feed-water Heater

Cold boiler feedwater is heated in two of these heat exchangers by the hot H_2O-H_2 vapor generated by the set of seven feed-water heater units, which, subsequent to cooling, is dispatched to the first stage of the H_2 products compressor-after-cooler complex. The heat exchangers are similar to the feed preheaters with the exception of the tube length (465 inch), number of tubes (10,940), shell dimensions (92 inch i.d., 1 inch wall thickness), overall dimensions (7.83 feet o.d. x 42.75 feet long), and external heat transfer surface (69,360 ft^2).

23.08 Hydrogen Plant

23.08.01 Vapor Compressors for the Hydrogen Conditioning System

A flow schematic for the hydrogen conditioning system is shown in Fig. C-1. The H_2-H_2O vapor is compressed to eliminate the water from the hydrogen product. Multistage turboblowers are specified. The blowers are assumed to have 70% overall efficiency. The turboblower design consists of eight stages connected in series with after-coolers interposed between stages. The design specifications and the operating parameters and costs of the various stages are summarized in Table C-1. The costing algorithm was applied to each stage as shown.

23.08.02 Intercooler--Condensers for Hydrogen Conditioning System

This is a set of heat exchangers that cool down the compressed H_2-H_2O vapor product and condenses out a portion of the eight compressor stages. Each unit has countercurrent flow of H_2-H_2O vapor down the outside of the tubes with upflow of cooling water through the tubes. The condensate generated is recycled back to the feed-water heater. The residual partially dehydrated H_2-H_2O stream is feed for the next compression stage.

All units are identical as to tube size, number of tubes, and configuration. The tubes are of the same design as those given in 23.05 with the following differences: 22,930 tubes per unit and shell i.d. of 132 inches. The tube length, shell wall thickness, and other parameters that vary from stage to stage are sumarized in Table C-2.

23.08.03 Vapor Compressors for Hydrogen Product Conditioning-Polishing

The raw H_2-H_2O vapor from stage eight of the compressor-intercooler is compressed to further eliminate the H_2O from the H_2 product. There are four

TABLE C-1

DESIGN AND OPERATING PARAMETERS FOR VARIOUS STAGES OF THE VAPOR COMPRESSORS FOR THE HYDROGEN CONDITIONING SYSTEM

Stage	Feed lb/hr	Feed mf H_2	Feed psia	Feed °F	Outlet psia	Outlet °F	Unit 10^3 BHP	Number	Required, ft per Unit	Cost 10^6 $
1	$6.134-10^5$	0.342	2.50	134.44	4.33	302.47	3.538	4	6.8x8.2	2.972
2	$4.336-10^5$	0.674	3.83	95.00	6.63	304.18	3.143	3	6.5x7.9	2.044
3	$3.004-10^5$	0.787	6.13	95.00	10.63	296.76	2.903	3	6.4x7.6	1.928
4	$2.258-10^5$	0.867	10.13	95.00	17.54	291.54	2.855	3	6.3x7.6	1.905
5	$1.834-10^5$	0.919	17.04	95.00	29.52	288.13	2.903	3	6.4x7.6	1.928
6	$1.955-10^5$	0.952	29.02	95.00	58.26	286.00	2.999	3	6.4x7.7	1.974
7	$1.452-10^5$	0.972	49.76	95.00	86.19	284.72	3.088	3	6.5x7.8	2.017
8	$1.372-10^5$	0.984	85.69	95.00	149.42	283.95	3.156	3	6.5x7.8	2.050
Total	---	---	---	---	---	---	---	25	---	16.818

TABLE C-2

SUMMARY OF DESIGN AND COSTING PARAMETERS FOR INTERCOOLER-CONSENSERS FOR HYDROGEN CONDITIONING SYSTEMS

	Stage								
	1	2	3	4	5	6	7	8	Totals
Desup. Tube Length, ft	6.335	5.531	6.297	6.060	12.811	15.972	23.545	98.760	
Conden. Tube Length, ft	43.311	32.342	20.276	45.431	8.942	5.843	3.841	6.071	
Total Tube Length, in.	596.0	455.0	319.0	618.0	261.0	262.0	329.0	1258.0	
Total Ht. Trans. Area, 10^5 ft^2	1.863	1.422	0.997	1.932	0.816	0.819	1.029	3.933	12.811
Shell Thickness, in.	1.00	1.00	1.00	1.00	1.00	1.50	1.50	1.50	
Shell, o.d., in.	134.0	134.0	134.0	134.0	134.0	135.0	135.0	135.0	
Overall Length, in.	644.0	503.0	367.0	666.0	309.0	310.0	377.0	1306.0	
Design Pressure, psia	100.00	100.0	100.0	100.0	100.0	100.0	130.0	220.0	
Y_0 Factor	1.50	1.50	1.25	1.50	1.25	1.25	1.50	2.50	
Exchanger Cost, $M	3.033	2.547	1.688	3.104	1.482	1.486	2.231	10.317	25.888

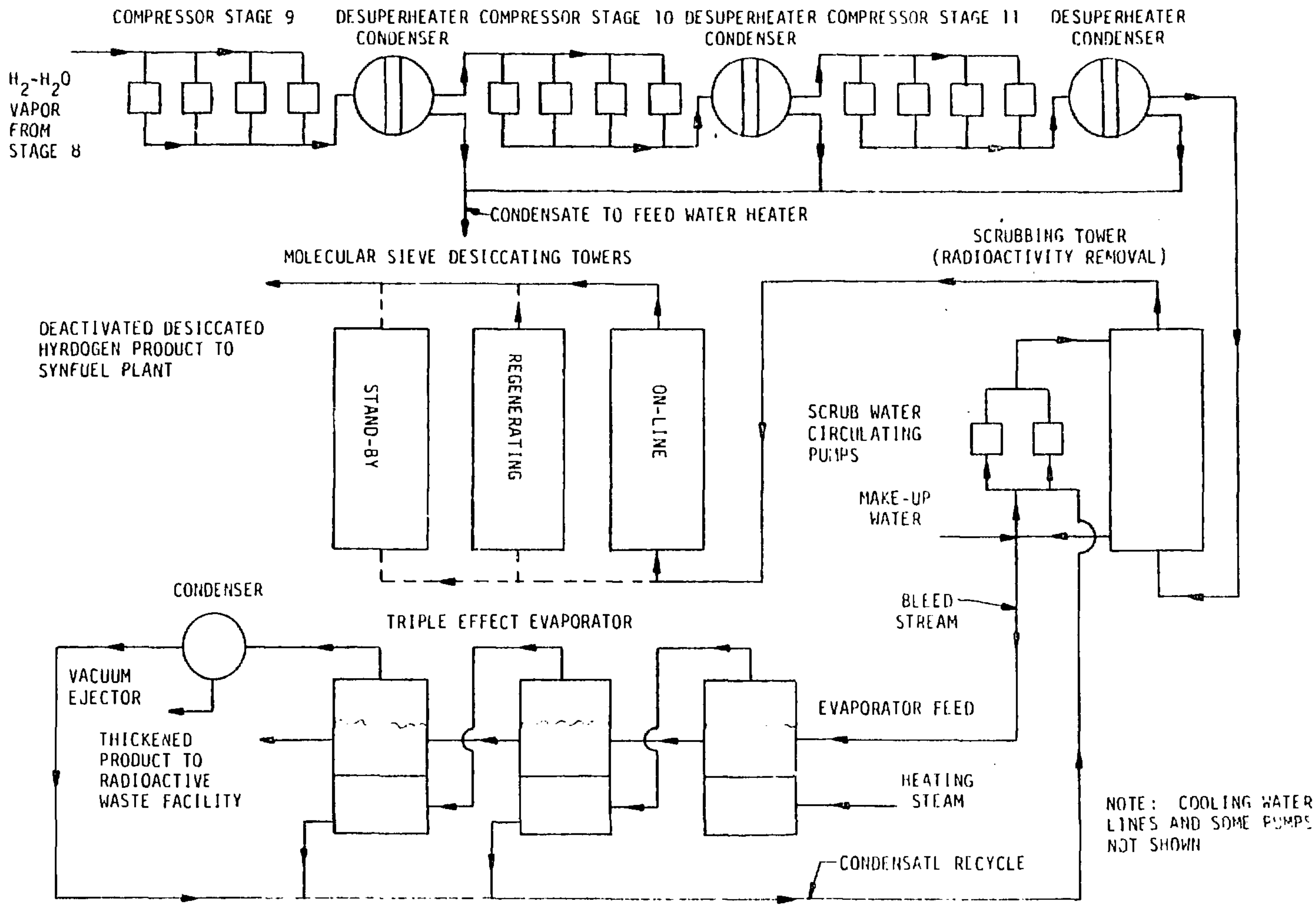

FIGURE C-1 Flow Schematic for Hydrogen Conditioning System compressors for each of the three stage turboblowers. The design pressure is 1150 psia. Seventy percent efficiency is assumed. The design parameters and estimated costs for each of the three stages is shown in Table C-3.

23.08.04 Intercooler-condensers for Raw Hydrogen Product Conditioning-polishing

This is a set of heat exchangers that cool down highly compressed H_2-H_2O vapor products and condenses out a portion of the contained water. One heat exchanger is provided for each of the three compressor stages. The design is identical to those described under 23.08.2. The design/operating parameters and the estimated costs are summarized in Table C-4.

23.08.05 Raw Hydrogen Product Scrubbing Tower

The raw hydrogen product is scrubbed to remove any radioactivity, using high-pressure water as the scavenging medium. The scrubbing tower is packed with pall rings. H_2-H_2O vapor from the 11th compressor-intercooler stage flows up the tower, countercurrent to the closed-cycle recirculating water. A bleed stream of the scrub water is fed to the evaporator. One inch pall rings are packed in the 8.69-foot-i.d. and the 41-foot-high tower. The H_2-H_2O vapor residence time over the packing is 15 sec. Overall tower dimensions are 9.1 foot o.d. (2.5 inch shell thickness) and 47 feet high. Two thousand four-hundred and thirty cubic feet of pall rings are used. The estimated cost of this packing is $\$67/ft^3$. The design pressure is 1150 psia. Two scrub water, 15 gpm--40 psia head canned motor circulating pumps (each with 0.53 BHP) are parts of the auxiliary equipment needed.

23.08.06 Evaporator for Deactivating Scrub Water

The evaporators are triple effect, forced circulation devices. They are of the vertical calandria, tube-in-shell design. Any radioactivity carried

TABLE C-3

SUMMARY OF DESIGN PARAMETERS AND COSTING FOR VAPOR

COMPRESSORS FOR HYDROGEN PRODUCT CONDITIONING-POLISHING

Item	Stage 9	Stage 10	Stage 11	Totals
Desuperheater Tube Length, ft	14.507	39.461	27.876	---
Condenser Tube Length, ft	7.745	5.263	3.073	---
Total Tube Length, in.	268.000	537.000	372.000	---
Total Ht Trans 10^5 ft^2	0.838	1.679	0.1163	2.633
Shell Thickness, in.	1.500	1.750	2.000	---
Shell o.d., in.	135.000	135.500	136.000	---
Overall Length, in.	316.000	585.000	420.000	---
Vapor Inlet, psia	147.920	255.500	441.500	---
Design Pressure, psia	380.000	660.000	1150.000	---
Y_o Factor	2.500	2.500	3.000	---
Exchanger Cost $\$10^6$	4.460	8.214	9.149	21.823

TABLE C-4

SUMMARY OF DESIGN, OPERATING, AND COST PARAMETERS
FOR INTERCOOLER-CONDENSERS FOR RAW HYDROGEN PRODUCT CONDITIONING-POLISHING

	Feed				Outlet		Unit		Required,	Cost
Stage	lb/hr	mf H_2	psia	°F	psia	°F	10^3 BHP	Number	ft per Unit	10^6 $
9	1.5218×10^5	0.99449	147.9	95.00	256.0	260.36	4.906	4	6.7x8.1	3.777
10	1.4803×10^5	0.99767	255.5	85.00	442.0	247.31	4.798	4	6.7x8.0	3.716
11	1.4675×10^5	0.99987	441.5	85.00	765.0	247.90	4.810	4	6.7x8.0	3.722
Total	---	---	---	--	---	---	---	12	---	11.215

in the raw H_2 product is trapped by the scrubbing tower water. Two hundred seventy-one vertical tubes, 4 feet long, 1 inch in diameter, made of SS-304, form the heat exchanger surface area of the evaporators per effect.

23.08.07 Final Hydrogen Product Drying Towers

Three drying towers are used to desiccate the final wet H_2 products subsequent to pressurized water scrubbing to eliminate any entrained radioactivity. While one unit is operating on stream, the second unit is undergoing desiccant regeneration, and the third is on standby. Molecular sieve beds are used as the desiccant. The tower shell is made of SS-304, 104 in. i.d., 2.5 in. wall thickness. Overall dimensions are 9.08-foot o.d. and 47 feet high. The desiccant volume is 2762 ft^3. The estimated cost of the molecular sieves is based on $223/$ft^3$. Auxiliary costs are assumed to be 7% of the cost of one tower.

23.08.08 High Temperature Electrolyzers

The high-temperature electrolyzers consist of 28 units. The electrolyzers were designed based on a current density of 0.5 A/cm^2 and a resistance of 3.07Ω/tube. Each electrolyzer cell is 1 cm long; 125 cells make up a tube. There are 225,360 tubes per unit. The electrolyzer area per cell is 4.442 cm^2. The tubes are 1.56 m long and four lenghts are fitted into the overall HTE. The tubes have 1.438 cm o.d. and 1 cm i.d. The overall dimensions of each unit are 6 o.d. x 19.5 m high and 8.9 cm wall thickness.

The cost estimates for the electrolyzers were based on materials costs and fabrication costs. The materials costs were based on large quantity purchases of the individual materials (adjusted 1982 Alpha prices). The amount of each type of material and the costing basis are tabulated in Table C-5.

TABLE C-5

SUMMARY OF MATERIALS COSTS PER HTE

Material	Amount Required, kg	Cost Per Unit Mass, kg	Material Cost, $
ZrO_2	1.7370×10^5	4.00	6.95×10^5
Y_2O_3	3.1070×10^3	97.33	3.0240×10^5
La_2O_3	1.7476×10^3	15.00	2.6195×10^4
Cr_2O_3	5.8253×10^2	5.00	2.9127×10^3
Al_2O_3	3.8833×10^5	5.33	2.0698×10^6
NCO	1.4563×10^4	11.00	1.6019×10^5
PrO_2	2.3301×10^3	136.00	3.1689×10^5

Total Oxide Materials' Costs	2.33×10^6
Oxide Tube Fabrication Cost	0.883×10^5
HTE Shell Cost	4.62×10^6
Total Cost/HTE Unit	7.73×10^6
Total HTE Cost (28 Units)	216.44×10^6