9. POWER CONVERSION

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Contents

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9.1. INTRODUCTION

For a commercial reactor design, the objective of power conversion is to convert the thermal power into electricity at the highest possible conversion efficiency. Higher efficiency leads to less thermal pollution and, in general, lower cost of electricity. The conversion efficiency of a thermal cycle is directly related to the temperature potential at which the thermal power is recovered from the reactor core. Therefore, the selection of a thermal cycle and the obtainable conversion efficiency are intimately related to the thermal-hydraulic design of the first wall, blanket, and divertor.

In the thermal-hydraulic design of the ARIES-I fusion power core, helium at 10-MPa pressure is used as the primary coolant. The total useful thermal power recovered by the primary coolant is 2544 MW, of which about 88% is recovered by the first-wall/blanket coolant circuit and the rest by the divertor coolant circuit. The inlet and outlet temperatures of the primary coolant are, respectively, 350 and 650 °C. The inlet temperature is chosen so as to optimize the power conversion efficiency and, at the same time, meet the thermal-hydraulic design constraints.

The particular combination of the primary coolant and its operating pressure, structural material, and coolant channel configuration has made the gas cooled design of the reactor core of ARIES-I with a coolant exit temperature of 650 °C possible. The structural material for the first wall and blanket and for the divertor plate is silicone-carbide composite. The divertor plate is coated with 2 mm of tungsten as the armor. Section 5 discusses the detailed design of the divertor plate and Sec. 8 with that of the first wall and blanket. Table 9.1-I shows the major parameters of ARIES-I that are relevant to the power conversion system.

The primary-coolant exit temperature of 650 °C is not high enough to necessitate consideration of such an advanced concept as plasma magnetohydrodynamic power conversion. However, this temperature is significantly higher than the maximum steam temperatures in the Rankine steam cycles presently used in the fossil-fuel power plants. Therefore, advanced conventional and nonconventional thermal power cycles have been considered for ARIES-I. This section presents the various thermal cycles that have been investigated, the selection of the reference cycle, and the results of the analysis of the reference cycle.

Table 9.1-I.
ARIES-I Parameters Relevant to the Power Conversion System

Fusion power (MW)	1,925
Blanket energy multiplication	1.3
Current-drive power (MW)	94
First-wall-/blanket-coolant pumping power (MW)	15
Divertor-coolant pumping power (MW)	35
Total useful thermal power (MW)	2,544
Primary coolant	Helium
Helium pressure (MPa)	10
Helium inlet temperature (°C)	350
Helium exit temperature (°C)	650

9.2. CANDIDATE POWER CYCLES

In order to select a suitable power-conversion system, the following three categories of thermal power cycles have been considered: dissociating-gas, inert-gas Brayton, and Rankine steam. The dissociating-gas cycles are nonconventional cycles; the inert-gas Brayton and Rankine steam cycles are conventional cycles that are presently in use for commercial power conversion.

9.2.1. Dissociating-Gas Cycles

Dissociating-gas cycles are under theoretical and experimental investigations. The working fluids in these cycles are chemically reacting gases that undergo endothermic dissociation reaction when heated (in the heat exchanger, regenerator, *etc.*) and exothermic recombination reaction when cooled (while expanding through the turbine). These gases have higher effective heat capacity and thermal conductivity, and smaller specific volume at low temperature compared to the commonly used inert gases. The dissociating gases also perform better than inert gases as coolants. Hasan and Martin [1] have addressed the issue of using dissociating gases as the primary coolant and working fluids in power cycles for fusion applications.

A partial list of the prospective dissociating gases is given in Table 9.2-I. Table 9.2-II provides the main physical properties of the two most widely studied prospective dissociating gases, nitrogen tetroxide (N_2O_4) and nitrosyl chloride ($NOC\ell$), for use both as heat transfer media and as working fluids for power cycles. These gases are, however, toxic and corrosive.

The gases in Table 9.2-I have large temperature ranges over which dissociation and recombination reactions take place. For example, for the N_2O_4 system, the dissociation and recombination reactions take place at up to ~850 °C at 1 atm pressure and 1200 °C at 100 atm pressure. Therefore, over a wide range, the favorable thermodynamic effects of the chemical reactions on the cycle efficiency can be realized. There are several such effects. Because of the decrease in the number of moles in the compressor (caused by recombination at low temperature), the compressor work is much less with a dissociating gas than with an inert gas. Regeneration is also more efficient because of the heat of

Table 9.2-I.
A Partial List of Dissociating Gases

Dissociating Gas	Gas-Constant Multiplication	ΔH_R (kcal/kg)	Temperature Range (°C)
$N_2O_4 \rightleftharpoons 2NO_2$	2	13.7	25 – 170
$2NO_2 \rightleftharpoons 2NO + O_2$	1.5	27.0	140 – 850
$2NOC\ell \rightleftharpoons 2NO + C\ell_2$	1.5	9.21	25 – 900
$A\ell_2Br_6 \rightleftharpoons 2A\ell Br_3$	2	30.0	300 – 1,400
$A\ell_2C\ell_6 \rightleftharpoons 2A\ell C\ell_3$	2	29.8	200 – 1,100
$A\ell_2Br_6 + 4A\ell(liq) \rightleftharpoons 6A\ell Br$	6	282.4	670 – 1,400
$A\ell_2C\ell_6 + 4A\ell(liq) \rightleftharpoons 6A\ell C\ell$	6	263.8	670 – 1,200

Table 9.2-II.
Properties of N_2O_4 and NOCℓ

Property	N_2O_4	NOCℓ
Molecular weight (g/mole)	92.02	65.46
Boiling point (°C)	21.3	–5.8
Melting point (°C)	–11.0	–61.5
Critical temperature (°C)	158.3	167.5
Critical pressure (atm)	103.3	90.0
Heat of reaction (kcal/kg)	149/293	141.7
Reaction process	$N_2O_4 \rightleftharpoons 2NO_2 \rightleftharpoons 2NO + O_2$	$2NOC\ell \rightleftharpoons 2NO + C\ell_2$
Temperature range (°C)		
1 atm	25 – 850	25 – 900
100 atm	25 – 1,200	—

reaction and better heat transfer capability of the dissociating gases. Because of higher heat capacity and smaller specific volume of the dissociating gases at low temperature, the low pressure turbine is smaller and has fewer stages than turbines that use steam or inert gas as the working fluid.

Of the two most-analyzed dissociating gases, NOCℓ is used in the Brayton cycle and N_2O_4 can be used in both Brayton and Rankine cycles. Typical predicted efficiencies for given maximum-cycle temperatures are shown in Table 9.2-III. In this table, NOCℓ-N_2O_4 stands for a compound cycle with a topping Brayton cycle using NOCℓ and a bottoming Rankine cycle using N_2O_4. A comparison of an N_2O_4 turbine and a steam turbine is shown in Table 9.2-IV.

The principal advantages of a dissociating-gas cycle are: (1) higher possible maximum cycle temperature and higher efficiency than the Rankine steam cycle, and (2) smaller turbine, regenerator, *etc.,* thus leading to a more compact design than either the inert-gas Brayton or the Rankine steam cycles. The main disadvantages are: (1) safety hazard

Table 9.2-III.
Typical Cycle Efficiency

Cycle Type	Maximum Cycle Temperature (K)	Efficiency [Ref.]
$NOC\ell$-N_2O_4	1,000	55% [3]
N_2O_4-N_2O_4	1,000	51% [3]
$A\ell Br_3$-N_2O_4	1,000	48% [3]
$A\ell_2Br_6$-N_2O_4	1,000	56% [2]
$NOC\ell$	900	40% [4]

Table 9.2-IV.
Turbine Parameters with N_2O_4 and H_2O as Working Fluids

	N_2O_4	Steam
Output (MW)	500	500
Throttle pressure (atm)	240	240
Throttle temperature (°C)	565	580
Exit pressure (atm)	1.4	0.035
Number of stages	10	42
Length (m)	16.8	29.1
Weight (tons)	180	964
Cost (1,000 rubles)	619	1,600

from the toxicity of N_2O_4 and NOCℓ, and (2) materials need to be developed, especially for high temperature applications.

9.2.2. Inert-Gas Brayton Cycle

A power plant based on the inert-gas Brayton cycle is more compact and can have a much higher maximum-cycle temperature than a Rankine steam plant. Open-cycle gas turbines, which are used in aircraft engines, have a maximum cycle temperature of about 1200 °C. Closed-cycle gas turbines (CCGT) are, however, limited to lower maximum temperatures. Existing fossil-fuel CCGT plants have a maximum temperature of about 750 °C. The maximum temperature for advanced coal-fired CCGT plants is expected to be about 850 °C. Even at this high temperature, the efficiency of CCGT is about 40% [6]. This is much lower than the efficiency of an advanced Rankine steam cycle with a maximum temperature of about 600 °C.

9.2.3. Rankine Steam Cycle

The Rankine steam cycle is used predominantly for power conversion in present-day fossil-fuel and nuclear power plants. For the same maximum cycle temperature, the Rankine steam cycle offers the highest efficiency of all of the thermal cycles. For the ARIES-I reactor, the dissociating-gas cycle was not selected primarily for safety reasons and because materials development is needed. In addition, the maximum cycle temperature that is possible for ARIES-I (~600 °C) can be utilized by an advanced Rankine steam cycle. The inert-gas Brayton cycle, although more compact, would provide much lower conversion efficiency than the Rankine steam cycle. Therefore, an advanced Rankine steam cycle is selected as the reference cycle for ARIES-I. The remainder of this section deals with the selection of an advanced steam cycle and an analysis of its performance.

9.3. STATUS OF ADVANCED RANKINE STEAM CYCLE

Both subcritical and supercritical steam plants are operational at present. In the U.S., 159 supercritical units are operational in 89 plants representing 15% of the total U.S. plants. The present-day standard supercritical Rankine cycle has steam conditions of 24.1 MPa/565.6/565.6/565.6 °C which means that the maximum throttle steam pressure is 24.1 MPa, there are two reheats, and the steam temperatures after superheat

(T_{SH}) and each reheat (T_{R1} and T_{R2}) are equal to 565.6 °C. The goal for the 1990s is to obtain the steam conditions of 27.6 to 34.5 MPa/593.3/593.3/593.3 °C. The Electric Power Development Co. of Japan is studying cycles with the steam conditions of 34.5 MPa/648.9/593.3/593.3 °C [9].

Currently, advanced supercritical steam cycles are operational primarily to test, gather data, and study technical issues and economic competitiveness. The Eddystone Station (unit-1) supercritical steam plant of the Philadelphia Electric Co. has the steam conditions of 34.5 MPa/648.9/565.6/565.6 °C [9]. It has been operating for over 20 years. Its capacity is 325 MWe and it has achieved an availability of 76%.

9.3.1. Findings of Studies Sponsored by EPRI

Electric Power Research Institute (EPRI) has sponsored a number of studies to assess the performance of fossil-fuel power plants and to develop advanced supercritical plants [7 - 10]. In one of these studies, Westinghouse Electric Co. performed an engineering assessment of pulverized-coal power plants [7] and found a reduction in levelized busbar cost of electricity (LB-COE) of 2.3 mills/kWh. It also found an 865-Btu/kWh improvement in heat rate as a result of switching from an existing base design with the steam conditions of 24.1 MPa/537.8/551.7/565.6 °C to an advanced design with the steam conditions of 31 MPa/593.3/565.6/565.6 °C. For advanced designs, the ratio of the decrease in fuel cost to the increase in capital cost varies from 2.74 to 6.69. The projected R&D cost is $14 M over a 5-to-6-year period.

The EPRI study also found that increases in temperature represent more of a technical challenge than do increases in throttle pressure. In the study, the maximum pressure is varied from 24 to 69 MPa and the maximum temperature from 538 to 760 °C. The limit on the maximum temperature (760 °C) is based on projections for the development of materials and manufacturing processes for the production of a high-temperature turbine rotor.

In a similar EPRI-sponsored study conducted by General Electric, Stone & Webster Engineering Corp., and Babcock & Wilcox Co. [8], the supercritical plants were categorized as three groups—current, advanced, and futuristic. Table 9.3-I shows some of the results of this study.

Table 9.3-I.
Results from an EPRI Study

Category	Steam Conditions ($MPa/T_{SH}/T_{R1}/T_{R2}$ °C)	Net Station Output (MWe)	Total LB-COE (mills/kWh)
Current	24.1/537.8/551.6/565.6	671.5	60.9
	31.0/537.8/551.6/565.6	671.5	59.6
Advanced	24.1/593.3/607.2/621.1	671.4	60.4
	31.0/593.3/621.1/648.9	672.9	60.9
Futuristic	44.8/648.9/690.6/732.2	674.7	72.5

Conclusions drawn from another study, performed by Gilbert Associates [9], for the development of advanced fossil-fuel power plants are:

1. Under the present/near-future conditions, the economically optimum cycle has the steam conditions of 31 MPa/593.3/593.3/593.3 °C.
2. The availability can be increased from the present 82.2% to 87.2%–88.2%.
3. A unit with a capacity of more than 800 MWe would require the expensive cross-compound arrangement of the turbines.
4. The 593.3 °C (1,100°F) temperature limit is because the coal-ash corrosion on the gas side would cause serious problems for reheaters beyond this temperature.
5. 12% Cr steel should be used to handle the ash corrosion of the superheater tubes.
6. For an 800-MWe plant, the direct cost of producing electricity is about $1.066/kWh.
7. Over the plant lifetime, it is estimated that switching to the optimum advanced steam plant will save between $59 and 97 M in fuel costs.

9.3.2. Advanced Steam-Cycle R&D Needs

The R&D efforts that are necessary for commercial application of the advanced, supercritical Rankine steam cycles are being made by the fossil-fuel power-conversion community. These efforts [7 - 10] include:

1. Better start-up control,
2. Improvement of wearability of the start-up system valves,
3. Improvement of cyclic-duty capability,
4. Control of stress-corrosion cracking of water-wall tubing in the steam generator,
5. Control of coal-ash corrosion of the tubes in the reheaters,
6. Better control of water quality,
7. Design of high-pressure/high-temperature feedwater heater and pump,
8. Reduction of solid particle erosion of the high-pressure turbine blades,
9. Reduction of stress corrosion of the turbine blades, and
10. Development of forging techniques for the rotor in tandem turbine arrangement.

9.3.3. Advanced Steam Cycle for ARIES-I

Results from the studies discussed in the previous section show that the selection of an advanced, supercritical Rankine steam cycle with parameters close to those recommended by the EPRI studies would be a conservative choice for ARIES-I. It is conservative because the EPRI recommendations are for meeting the requirements of the fossil-fuel power plants in the next 20 to 30 years, and the time scale for the introduction of the first commercial fusion-reactor power plant is probably longer than 30 years from now. The final selection of the power cycle for ARIES-I has been made after some parametric studies and after considering the recommendations of the EPRI-sponsored studies.

Variations of gross cycle efficiency with maximum-throttle steam temperature and pressure are shown in Fig. 9.3-1. These results were obtained by using the computer code PRESTO [11]. The gross efficiency increases with both maximum cycle pressure

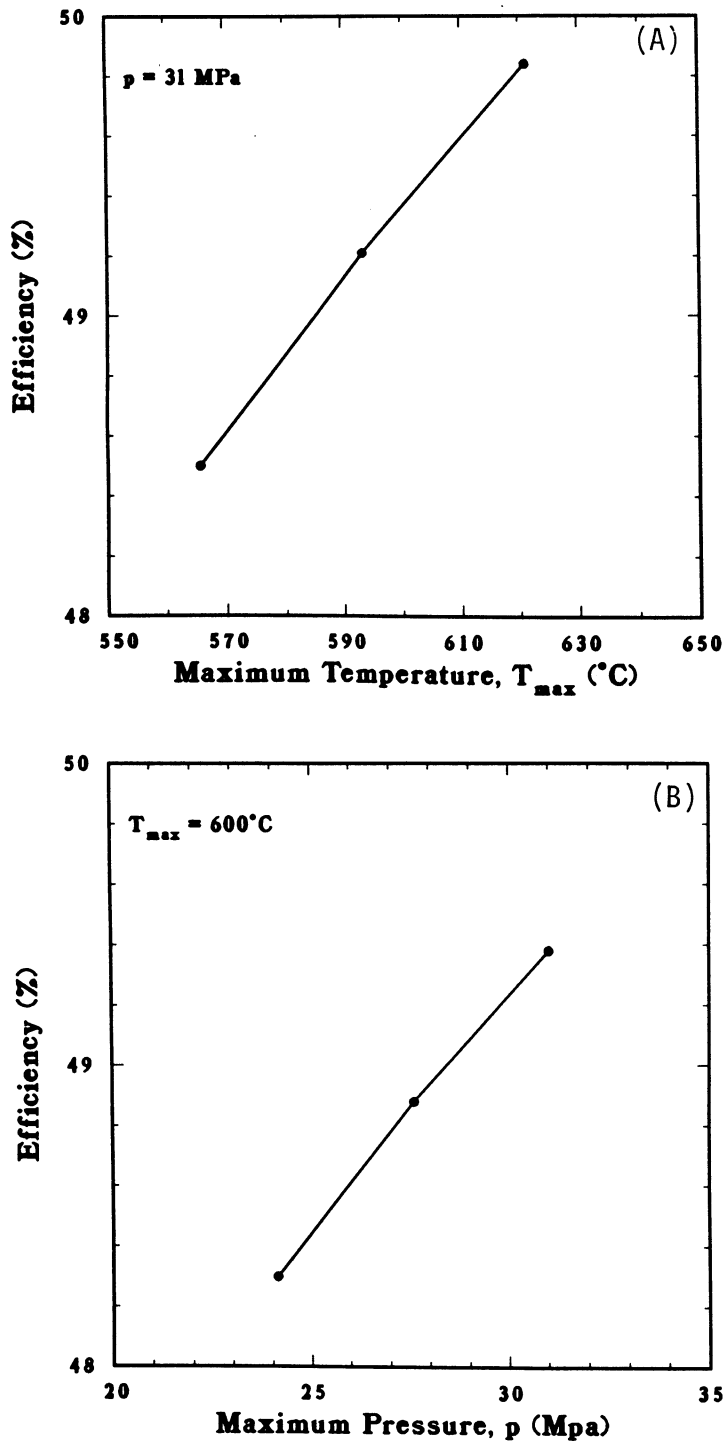

Figure 9.3-1. Gross thermal efficiency of cycles with nine feedwater heaters and two reheaters ($T_{SH} = T_{RH1} = T_{RH2}$) as functions of (A) maximum-throttle temperature and (B) maximum-throttle pressure.

and temperature. A gross efficiency of about 49% can be obtained with an advanced steam cycle that has parameters close to those recommended by the EPRI study.

The main parameters of the selected steam cycle for ARIES-I are:

1. Steam conditions: 31 MPa/600/600/600 °C (4500 psia/1112/1112/1112°F),
2. Two reheats,
3. Nine regenerative feedwater heaters, and
4. Condenser back pressure of 678 Pa (2 inches of mercury).

The objective has been to stay close to the recommended cycle in the EPRI study. It can be expected that the necessary R&D efforts for commercialization of the selected power cycle will be done by the fossil-fuel power community well before fusion power becomes commercially available.

9.4. ANALYSIS OF THE REFERENCE POWER CYCLE

The thermodynamic analysis of the thermal power cycle was performed using the code PRESTO [11]. The minimum temperature difference between the primary coolant and steam is kept at ~50 °C. Figure 9.4-1(A) is a schematic diagram of the power cycle with the superheater and the reheaters in conventional series arrangement. Figure 9.4-1(B) is the corresponding temperature-energy diagram. In order to realize the maximum steam temperature of 600 °C after superheat and after each of the two reheats, the maximum helium temperature must be 750 °C. Figure 9.4-2 shows the corresponding diagram for parallel arrangement of the superheater and reheaters. With this arrangement, steam temperature of 600 °C can be obtained from helium at a maximum temperature of 650 °C. Lowering the maximum helium temperature from 750 to 650 °C improves the thermostructural design of the blanket by increasing the safety factor. Therefore, the non-conventional parallel arrangement of the superheater and reheaters has been selected for the reference power cycle for ARIES-I.

The fractions of parallel mass-flow rates of helium through the superheater and reheaters are, respectively, $m_{SH} = 64\%$, $m_{RH1} = 22\%$, and $m_{RH2} = 14\%$. In order to stay within the 800-MWe limit for a single unit, two turbine-generator units, each using one-half of the reactor thermal power, are utilized. The turbines are arranged in tandem in each unit. The gross thermal efficiency is 0.49. These major parameters of the ARIES-I power conversion system are summarized in Table 9.4-I.

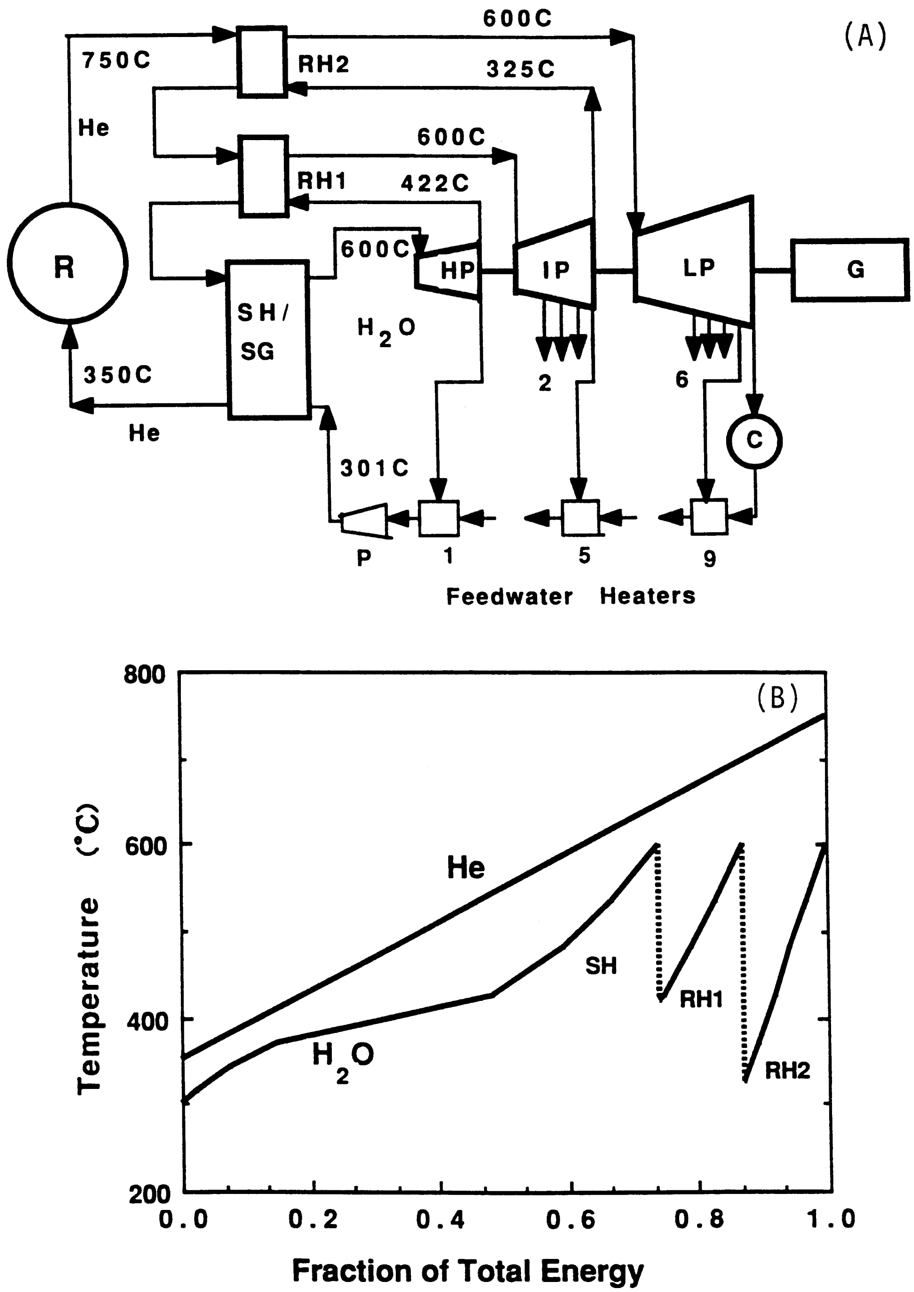

Figure 9.4-1. (A) Schematic flow diagram of the power cycle with the reheaters and the superheater in series (R=reactor core, SG=steam generator, SH=superheater, RH1=first reheater, RH2=second reheater, HP=high-pressure turbine, IP=intermediate-pressure turbine, LP=low-pressure turbine, G=electric generator, C=condenser, and P=feedwater pump). (B) Temperature-energy diagram for the cycle with the superheater and reheaters in series ($T_{SH} = T_{RH1} = T_{RH2} = 600\,°C$, 9 feedwater heaters, and 31 MPa steam pressure). The maximum helium temperature required is 750 °C.

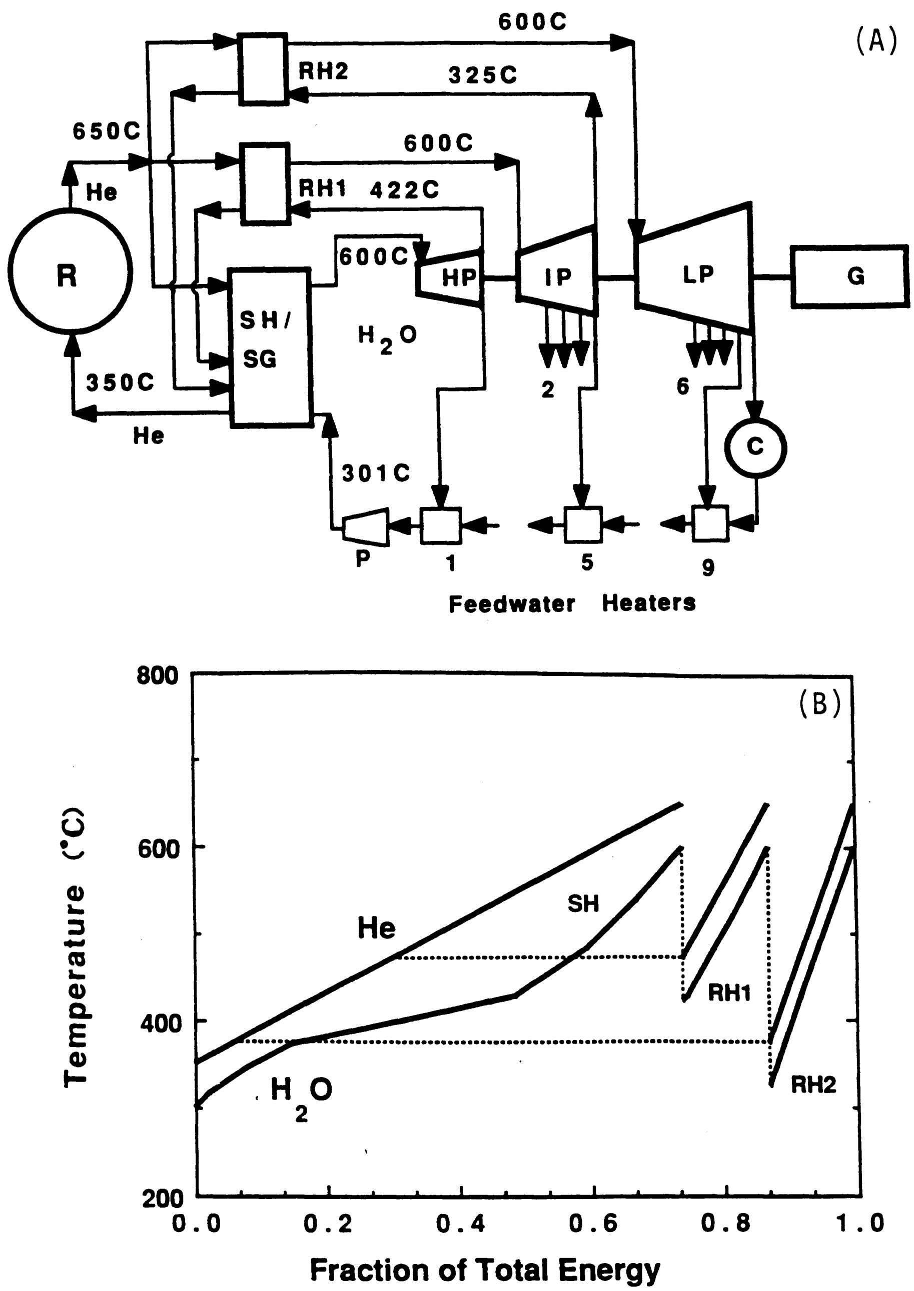

Figure 9.4-2. (A) Schematic flow diagram of the power cycle with the reheaters and superheater in parallel (R=reactor core, SG=steam generator, SH=superheater, RH1=first reheater, RH2=second reheater, HP=high-pressure turbine, IP=intermediate-pressure turbine, LP=low-pressure turbine, G=electric generator, C=condenser, P=feedwater pump). (B) Temperature-energy diagram for the power cycle with the reheaters and superheater in parallel (m_{SH} = 64%, m_{RH1} = 22%, m_{RH2} = 14%), 9 feedwater heaters, and 31 MPa steam pressure. Maximum helium temperature of 650 °C can be allowed.

Table 9.4-I.
Major Parameters of the ARIES-I Power Conversion System

Total helium flow rate (kg/s)	1,631
Total steam flow rate (kg/s)	892
Number of turbine-generator sets	2
Arrangement of the turbines	Tandem
Number of reheats	2
Number of regenerative feedwater heaters	9
Steam conditions	
Maximum throttle pressure (MPa)	31
Temperature after superheat (°C)	600
Temperature after 1st reheat (°C)	600
Temperature after 2nd reheat (°C)	600
Extraction pressures (MPa)	
Heater 1	9.0
Heater 2	3.8
Heater 3	2.4
Heater 4	1.7
Heater 5	1.14
Heater 6	0.47
Heater 7	0.26
Heater 8	0.14
Heater 9	0.048
Condenser back pressure (MPa)	0.0067
Feedwater inlet temperature (°C)	301
Gross thermal efficiency	0.49
Recirculating power fraction	0.2
Net plant efficiency	0.39
Net electric power (MW)	1,000

9.5. CONCLUSIONS

An advanced, double reheat, supercritical Rankine steam cycle is selected for converting the thermal power of ARIES-I. There are nine regenerative feedwater heaters and the condenser back pressure is 678 Pa (2 inches of mercury). The steam conditions are 31 MPa/600/600/600 °C, similar to those of the advanced cycle recommended by several EPRI studies. The power cycle analysis was performed by using the PRESTO code. The minimum temperature difference between helium and steam is kept at $\sim$ 50 °C. The maximum steam temperature is obtained from the primary-coolant exit temperature of 650 °C through the use of nonconventional, parallel arrangement of the superheater and reheaters. The gross efficiency of this advanced cycle is 0.49. The recirculating power fraction of the ARIES-I reactor is 0.2, and is primarily used for the current-drive system. The result net plant efficiency is 0.39 and the net electric power produced is 1000 MWe.

The research and development efforts necessary to commercialize the advanced steam cycle are being made by the fossil-fuel power-plant community. Because of the clean source of heat (He gas) for the power conversion system of ARIES-I, coal-ash corrosion of the superheater or reheater tubes is not a problem. Therefore, the possibility of attaining maximum steam temperatures higher than 600 °C, which would raise the conversion efficiency close to 50%, with the same technology and materials as for the EPRI-recommended advanced steam cycle should be investigated. The feasibility and economics of using high-temperature ceramic heat exchangers and turbines, which could raise power conversion efficiency above 50%, should also be explored for fusion application. Adequate lead time for such R&D can be assumed in view of the timetable for the expected appearance of commercial fusion-reactor power plants.

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