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Regenerative Heater Optimization for Steam Turbo-Generation Cycles of Generation IV Nuclear Power Plants

with a Comparison of Two Concepts for the Westinghouse International Reactor Innovative and Secure (IRIS)

August 2002

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UT-BATTELLE

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REGENERATIVE HEATER OPTIMIZATION FOR STEAM TURBO-GENERATION CYCLES OF GENERATION IV NUCLEAR POWER PLANTS
WITH A COMPARISON OF TWO CONCEPTS FOR THE WESTINGHOUSE INTERNATIONAL REACTOR INNOVATIVE AND SECURE (IRIS)

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CONTENTS

ACRONYMS AND SYMBOLS

HTGR – High Temperature Gas-cooled Reactor
IRIS – International Reactor Innovative and Secure
LMR - Liquid Metal-cooled Reactor
LOCA – Loss of Coolant Accident
LWR - Light Water-cooled Reactor
MSR – Moisture Separation Reheater
NERI – Nuclear Energy Research Initiative
NESLS - Nuclear Engineering Student Laboratory Synthesis
ORNL - Oak Ridge National Laboratory
PWR – Pressurized Water Reactor
RSICC - Radiation Safety Information Computational Center
SG – Steam Generator
USDOE – United States Department of Energy
UTK – University of Tennessee, Knoxville

A – Surface area of heater
B – Capitalized value of change in heat rate
C_n –Total enthalpy rise across the heater
F – Salisbury leverage factor
F_n – Drain flow leaving heater
G_n – Change in heat rate due to change in drain cooler terminal temperature difference
h – enthalpy
H – Reference cycle heat rate
H_n – Change in heat rate due to change in terminal temperature difference
I – Value of incremental power
K – Net output of reference cycle
LMTD – Log mean temperature difference
L_n – Enthalpy rise across drain cooling section
Q_n – Total feedwater flow rate
R_n – Enthalpy rise across condensing section
S – Incremental heater surface capital cost
T_n – Terminal temperature difference
U – Overall heat transfer coefficient
Y_n –Drain cooler terminal temperature difference

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I would like to acknowledge the following people for their help during my NESLS internship at ORNL: Ham Hunter, Nancy Hatmaker, Jess Gehin, Dan Ingersoll, and Jennifer Manneschmidt. I would also like to thank J. L. Walker of Northrop Grumman Newport News Shipbuilding for his generous help concerning steam cycles. I would finally like to thank professors, Dr. Larry Townsend and Dr. Fred Mynatt for their continued support of this research.

ABSTRACT

The intent of this study is to discuss some of the many factors involved in the development of the design and layout of a steam turbo-generation unit as part of a modular Generation IV nuclear power plant. Of the many factors involved in the design and layout, this research will cover feed water system layout and optimization issues. The research is arranged in hopes that it can be generalized to any Generation IV system which uses a steam powered turbo-generation unit. The research is done using the ORCENT-II heat balance codes and the Salisbury methodology to be reviewed herein.

The Salisbury methodology is used on an original cycle design by Famiani for the Westinghouse IRIS and the effects due to parameter variation are studied. The vital parameters of the Salisbury methodology are the incremental heater surface capital cost (S) in $/ft^2, the value of incremental power (I) in $/kW, and the overall heat transfer coefficient (U) in Btu/ft^2-°F-hr. Each is varied in order to determine the effects on the cycles overall heat rate, output, as well as, the heater surface areas. The effects of each are shown in the following tables:

Variation of incremental heater cost

S ($/ft^2)	35	45	55
Heat rate (Btu/kWh)	9870	9875	9880
Output (kW)	343,635	343,472	343,283
Surface area (ft^2)	147,546	133,442	97,832

Variation of incremental power cost

I ($/kW)	950	1050	1150
Heat rate (Btu/kWh)	9872	9870	9869
Output (kW)	343,561	343,635	343,679
Surface area (ft^2)	147,297	147,546	152,819

Variation of overall heat transfer coefficient

U (Btu/ft^2-°F-hr)	T_n 550 and Y_n 350	T_n 650 and Y_n 450	T_n 750 and Y_n 550
Heat rate (Btu/kWh)	9874	9870	9869
Output (kW)	343,528	343,635	343,679
Surface area (ft^2)	185,283	147,546	133,945

Then the methodology is then used to compare the optimized original Famiani design consisting of seven regenerative feedwater heaters with an optimized new cycle concept, INRC8, containing four regenerative heaters. The results are in the following table:

Comparison of Famiani and INRC8 cycles

Cycle	Famiani	INRC8	Difference
Heat Rate (Btu/kWh)	9870	9970	1.01 %
Output (kW)	343,635	340,219	-0.99 %
Surface Area (ft^2)	147,546	164,259	11.33 %

It can be seen that a trade between the complexity of the seven stage regenerative Famiani cycle and the simplicity of the INRC8 cycle can be made. It is desired that this methodology can be used to show the ability to evaluate modularity through the value of size a complexity of the system as well as the performance. It also shows the effectiveness of the Salisbury methodology in the optimization of regenerative cycles for such an evaluation.

1. INTRODUCTION

The intent of this study is to discuss one of the many factors involved in the development of the design and layout of a steam turbo-generation unit as part of a modular Generation IV nuclear power plant. This report covers issues involved in regenerative or feedwater system layout and optimization and a methodology for design work. The research is arranged in hopes that it can be generalized to any Generation IV system which uses a steam powered turbo-generation unit. However the methods are utilized here on conceptual designs for the Westinghouse International Reactor Innovative and Secure (IRIS). The effects of variation of some of the main parameters used in the method are shown. Also, the methods are used to do a small comparative analysis of two plant designs, a complex more thermally efficient design and a simpler less efficient design. It is desired that this research can be used to help make trade-off decisions for modularized Generation IV nuclear power systems.

This work is under the funding of the Oak Ridge National Laboratory (ORNL) Radiation Safety Information Computational Center (RSICC) Nuclear Engineering Student Laboratory Synthesis (NESLS) internship program. This study is an extension of the two years of work begun under the United States Department of Energy (USDOE) Nuclear Energy Research Initiative (NERI) program grant number DE-FG03-00SF22168 (Mynatt, 2000). This research grant is under the leadership of the University of Tennessee, Knoxville (UTK) Nuclear Engineering Department and involves design and layout concepts of compact, factory-produced, transportable, Generation IV reactor systems. The grant involves three groups each covering its own system as follows: gas cooled (HTGR) concept by MIT, liquid metal cooled (LMR) concept by UTK, and light water cooled (LWR) concept by UTK. The objectives of each group were to develop the conceptual designs and layouts for said systems and refine them through interaction with various industrial partners for the first two years and then the third and final year all three designs are to be evaluated by the UTK industrial engineering group.

The design under evaluation for this study is from the UTK LWR group, however the methodology can be generalized and used for any steam system. This LWR concept uses the Westinghouse International Reactor Innovative and Secure (IRIS) concept as the primary component. This concept is a pool-type pressurized water reactor (PWR) capable of producing 1000 MW of thermal power per unit. Many partner groups are working in the IRIS consortium on various aspects of the system. A list of some of the technical publications for this system can be found in the reference section, from which the general design information is obtained, for this research.

This document is split into four sections. Section 2 gives a brief description of the design parameters to be used in this study. Section 3 shows the development of the Salisbury methodology used in the study as well as a description of the ORCENT-II computer code. Section 3 also shows the methodology in use for the optimization, the effects of parameter variation and a comparison of two designs. Section 4 states the conclusions and summarizes the work presented as well as proposes any future work.

2. DESCRIPTION OF WESTINGHOUSE IRIS

As stated in the introduction the Westinghouse IRIS is used as the primary component for this study. The selection of the IRIS by the UTK team was "due to its innovative design and its compliance with Generation IV reactor goals" (Williams, 2002). The key difference between IRIS and other pool-type PWRs is its integral design. The integral design encloses the steam generators (SGs) as well as the primary pumps inside the primary pressure vessel. This eliminates the possibility of large break loss of coolant accidents (LOCA) in primary looping a major design concern in PWR technology. Originally in 1999 the IRIS was proposed as a modular 300 MW thermal power unit to be deployed by 2010. Since then it has been modified to 1000 MW of thermal power output. The IRIS has undergone various other design modifications mainly involving the steam generators. In 2002, the reference design has been determined to be a system of 8 helical tube SGs with parameters as shown in Table 1. These values are used as a steady state for all of the heat balance calculations to be performed in this study. Figure 1 is a simplified 3D rendering of the IRIS reactor.

Table 1: IRIS steam generator parameters[†]

Total thermal power	1000 MW (3.415 x 10^9 Btu/hr)
Thermal power per module	125 MW (4.269 x 10^8 Btu/hr)
Feedwater temperature	212 °C (435.2 °F)
Exit steam pressure	58 bar (841.219 psi)
Exit steam temperature	317 °C (602.6 °F)
Steam mass flow rate	500 kg/s (3968320.7 lb/hr)

[†]*Referenced from (Famiani, 2002)*

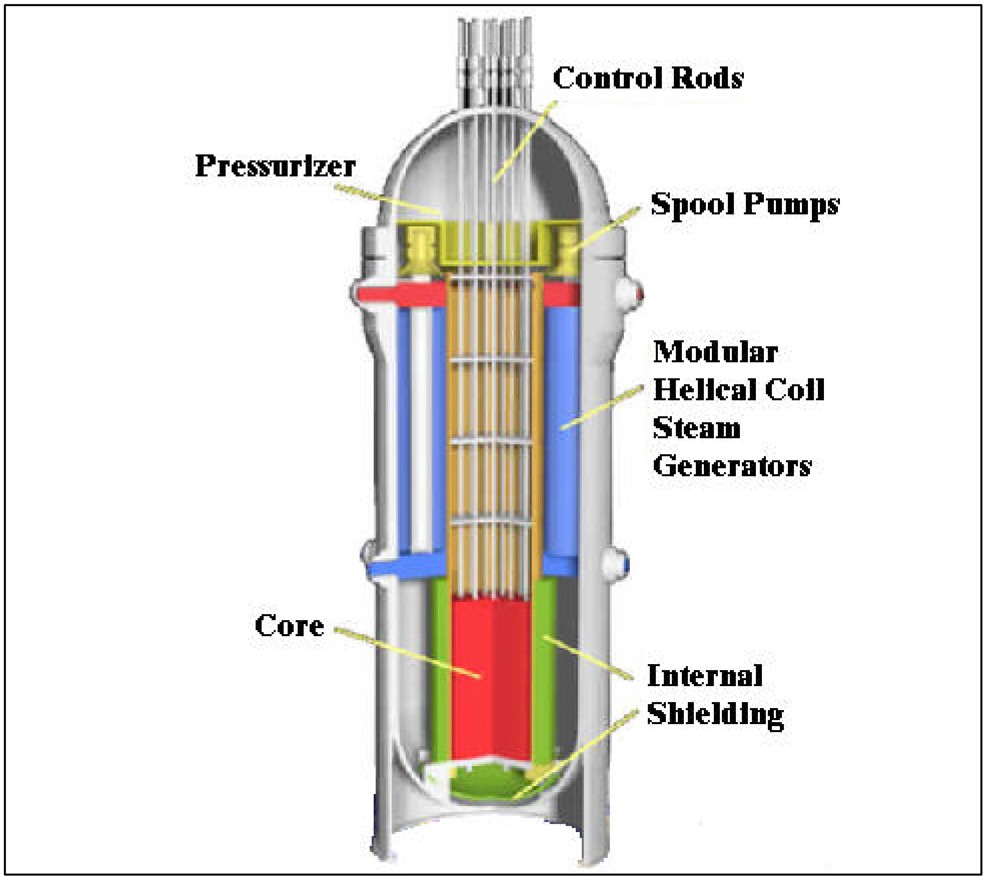

Figure 1: Simplified 3D cutaway model of IRIS‡
‡***(http://hulk.cesnef.polimi.it/iris_project_intro.htm)***

3. ANALYSIS

3.1 SALISBURY METHOD AND ORCENT-II

In his book, *Steam Turbines and Their Cycles* (Salisbury, 1974), J.K. Salisbury develops a methodology for the optimization of heater design conditions in power plant cycles. This methodology uses the economics of the cycle versus the capital cost of the cycle in order to determine the optimized regenerative heating parameters. The optimization involves the modification of the terminal temperature differences (T_n and Y_n) for each feedwater heater. At constant heater pressure, a decrease in T_n causes an increase in the exit enthalpy (h) and therefore causing the heater to require more extraction steam from the turbine. This, in turn, increases the inlet h for the next higher feedwater heater and therefore causes it to use less extraction steam from the turbine. The objective is to shift the extraction quantities down to lower pressure stages in order to utilize more of the steam for power production. However, the drain cooler terminal temperature difference (Y_n) offsets this effect somewhat and therefore adds more complexity to the problem.

In order to optimize the T_n and Y_n several factors must be first determined. A determination of the amount of change in heat rate of the total system caused by a degree change in temperature of the T_n (H_n) and Y_n (G_n) must be determined through heat balance calculations. Therefore one must first determine a reference cycle with generic T_n and Y_n estimates in order to determine a value for each heaters' terminal temperature difference effect on the heat rate (H_n and G_n). It is customary to modify the extraction pressures in order to create equal enthalpy rise or temperature rise of the feedwater across each of the regenerative heaters. The typical generic values used for the heaters are 5°F for T_n and 10°F for Y_n. Assuming the change in heat rate due to a change in T_n or Y_n is linear, the effect of changing the T_n or Y_n separately for each heater across a range of temperatures is done. The resulting effect on the heat rate (H_n and G_n) is obtained through heat balance calculation and would be extremely time consuming without the utilization of a computer program. The resulting H_n and G_n are used in the calculation of the optimal T_n and Y_n in Eq. 6 and Eq. 7. There are two main factors in the optimization of the cycle, one is the incremental heater surface capital cost (S) in $/ft^2. The second is a leverage factor (F) developed by Salisbury in order to aid in analytical calculation of cycle cost. This value is determined by a combination of capitalized value of heat rate change (B) in $/Btu/kWh, the value of incremental power (I) in $/kW, the reference cycle heat rate (H) in Btu/kWh and the net output of the reference cycle (K) in kW. The equation for F is shown as Eq. 1.

$$F = 1 + \left(\frac{K}{H}\right)\left(\frac{I}{B}\right) \qquad \text{(Eq. 1)}$$

Finally the overall heat transfer coefficient (U) for each heater must be known in order to determine the size of the surface area. This value is typically found experimentally for specific heat exchanger designs and is difficult to determine analytically. Therefore, for this study the average values of 650 Btu/ft^2-°F-hr and 450 Btu/ft^2-°F-hr recommended by Salisbury are used for the initial T_n and Y_n respectively. With the prior factors known, the calculation of the optimized regenerative cycle can be performed.

In order to calculate the optimized terminal temperature differences the enthalpy rise must be determined for both the condensing (R_n) and drain cooling (L_n) sections separately. This can be done with Eqs. 2 and 3 respectively where C_n is the total enthalpy rise across the heater, Q_n is the total feedwater flow through the heater and F_n is the drain flow leaving the heater.

$$R_n = C_n - L_n \qquad \text{(Eq. 2)}$$

$$L_n = \frac{C_n - (Y_n - T_n)}{Q_n / F_n} \qquad \text{(Eq. 3)}$$

With the values determined from Eqs. 2 and 3, the surface area of the heater (A) can be found by the log mean temperature difference (LMTD) method as shown in Eqs. 4 and 5. Finally the optimum T_n can be found using Eq. 6 and the optimum Y_n by Eq. 7.

$$LMTD = \frac{R_n}{\log(1 + R_n / T_n)} \qquad \text{(Eq. 4)}$$

$$A = \frac{Q_n \cdot R_n}{U \cdot LMTD} \qquad \text{(Eq. 5)}$$

$$Optimum T_n = \frac{R_n}{2}\left(\sqrt{1 + \frac{4 \cdot S \cdot Q_n}{U \cdot H_n \cdot B \cdot F \cdot R_n}} - 1\right) \qquad \text{(Eq. 6)}$$

$$OptimumY_n = \frac{L_n\left(\frac{Q_n}{F_n}-1\right)}{2}\left(\sqrt{1+\frac{4\cdot S\cdot Q_n}{U\cdot G_n\cdot B\cdot F\cdot L_n\left(\frac{Q_n}{F_n}-1\right)^2}}-1\right) \quad \text{(Eq. 7)}$$

These values for T_n and Y_n can be substituted back into the heat balance in order to determine the new optimized heat balance as well as the new feedwater heater surface areas. It is important to note that when the T_n and Y_n are modified for the highest-pressure feedwater heater, the steam generator inlet conditions will change. In order to maintain the original steam generator conditions the extraction pressure for this heater must be modified. This is done in an iterative manner until the original value is regained.

This methodology will be referred to as the Salisbury method throughout the remainder of this document. It is used to optimize each cycle that is presented in the following sections. It is important to note the multiple variables and non-linearity of this method makes for iterative procedures and it is very important to use a heat balance computer program like ORCENT-II. The following is the abstract from the ORNL ORCENT-II user manual (Fuller, 1979):

> "The ORCENT-II digital computer program will perform calculations at valves-wide-open design conditions, maximum guaranteed rating conditions, and an approximation of part-load conditions for steam turbine cycles supplied with throttle steam characteristic of contemporary light-water reactors. Turbine performance calculations are based on a method published by the General Electric Company. Output includes all information normally shown on a turbine-cycle heat balance diagram. The program is written in FORTRAN IV for the IBM System 360 digital computers at the Oak Ridge National Laboratory."

This code is obtainable from the ORNL RSICC Peripheral Shielding Routine Collection. This code has been updated and compiled into a DOS executable using FORTRAN 77 without any major modifications for use in this study. The most important output to be used for this research is the overall heat rate and net output of the turbine-generator as well as the inlet and outlet conditions of the regenerative heaters.

3.2 PARAMETER VARIATION EFFECTS

Three of the vital parameters of the Salisbury methodology are, as stated previously, the incremental heater surface capital cost (S) in $\$/ft^2$, the value of incremental power (I) in \$/kW, and the overall heat transfer coefficient (U) in Btu/ft^2-°F-hr. It is important for one to know the effects of each of these parameters on the cycle as a whole in order to make effective design decisions. Therefore, each is varied in order to determine the effects on the cycles overall heat rate, output, as well as, the heater surface areas. This is performed using the cycle proposed by Famiani (to be described later). Table 2 shows the effect of varying the incremental heater surface area capital cost from the original \$35/ft^2 to \$55/ft^2. It can be seen that, depending on the heater cost, the surface area can be substantially decreased without causing major decreases in the heat rate and output. Table 3 shows that the variation of incremental power cost, I, causes less of a change in the size of the heat exchangers as well as the output. Finally in Table 4, the heat transfer coefficients, U, are varied for both T_n and Y_n. Decreasing the value has more of an effect that increasing it on the surface areas. Neither greatly changes the output of the system.

Table 2: Variation of incremental heater cost

S (\$/ft^2)	35	45	55
Heat rate (Btu/kWh)	9870	9875	9880
Output (kW)	343,635	343,472	343,283
Surface area (ft^2)	147,546	133,442	97,832

Table 3: Variation of incremental power cost

I (\$/kW)	950	1050	1150
Heat rate (Btu/kWh)	9872	9870	9869
Output (kW)	343,561	343,635	343,679
Surface area (ft^2)	147,297	147,546	152,819

Table 4: Variation of overall heat transfer coefficient

U (Btu/ft^2-°F-hr)	T_n 550 and Y_n 350	T_n 650 and Y_n 450	T_n 750 and Y_n 550
Heat rate (Btu/kWh)	9874	9870	9869
Output (kW)	343,528	343,635	343,679
Surface area (ft^2)	185,283	147,546	133,945

3.3 COMPARISON OF CONCEPTUAL DESIGNS

As stated earlier the Salisbury methodology is now used to make a comparison of two conceptual steam plant designs for the Westinghouse IRIS. The first design is using the reference design as proposed by Famiani in the document *Steam Cycle and BOP Calculations for IRIS* (Famiani, 2002). The study by Famiani is to assist in the comparison in trade-off between steam generator size and regeneration rate. The conceptual design in this study is for an 1800-RPM dual flow high-pressure turbine with two dual flow low-pressure turbines. The unit has a steam moisture separator reheater (MSR) and seven regenerative feedwater heaters (six closed and one deaerator). The condenser operates at 0.08465 bar (1.227745 psi) and 42.6 °C (108.68 °F). It is important to mention that this cycle mimics the cycle used for the Westinghouse AP600. The AP600 unit is designed for nearly 2000 MW of thermal output. It is also important to note that the design by Famiani utilizes the old IRIS design value for steam generator exit steam pressure of 7 MPa (1015.2285 psi), in this study it is converted to the new pressure of 5.8 MPa (841.219 psi). The second design is a new design being proposed for this study alone called INRC8. It hopes to encompass the idea of modularity as less complex. This concept consists of one dual flow high-pressure turbine and one dual flow low-pressure turbine. It also proposes single stage MSR and four regenerative heaters. This concept keeps the same condenser parameters as the first design. The two designs can be seen in schematic form in Figure 2. Utilizing the above methods the two designs can be compared. A key point is the maintenance of the steam generator conditions. Each cycle is evaluated as follows in Table 5.

The important differences are that the net output is about 1% less for the INRC8 as compared to the Famiani design. There is an increase of 11% more surface area in the INRC8 heaters but the reduction in complexity could outweigh these effects. It is important to note that for each feedwater heater there are at least four piping runs that need to be added just for the main steam. This does not include the sensors and auxiliary equipment needed. This means that there are also only four units instead of seven to be moved and more of the cycle would be contained per module. Another important finding is that in order to decrease the surface area of the feedwater heaters; the steam generator conditions must be modified. It might be worthwhile to study the effectiveness of reducing the steam generator inlet temperature and losing some of the efficiency in order to reduce the size of the overall plant. The primary purpose of this small study is to show the possibilities for complexity reduction as an important idea in modularity as well as size reduction.

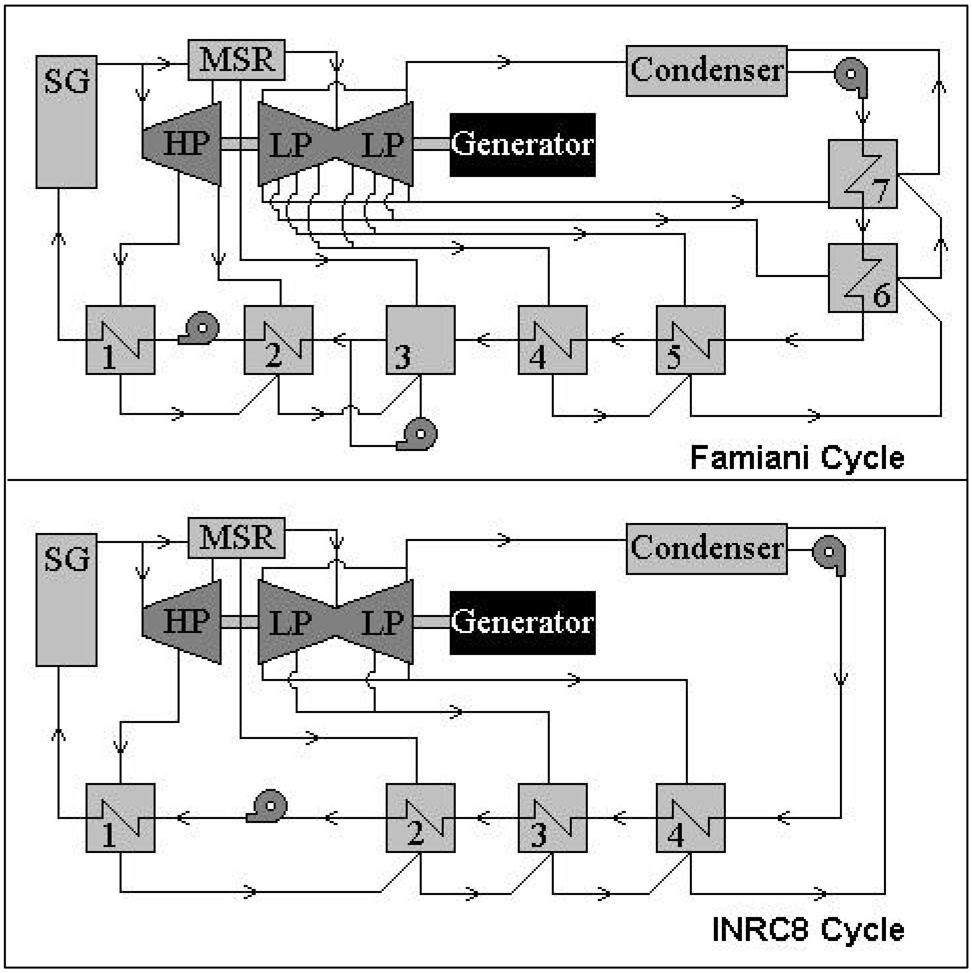

Figure 2: Schematics of Famiani and INRC8 Cycles

Table 5: Comparison of Famiani and INRC8 cycles

Cycle	Famiani	INRC8	Difference
Heat Rate (Btu/kWh)	9870	9970	1.01 %
Output (kW)	343,635	340,219	-0.99 %

Surface Area (ft^2)	147,546	164,259	11.33 %

4. CONCLUSIONS

The Salisbury method is very helpful in quickly determining the optimum heater design conditions for nuclear steam plants. Using this method in conjunction with a heat balance computer program like ORCENT-II, one can quickly and easily analyze multiple plant designs. The effects of variation of the key parameters from this study can be used to help in determination of various trade-off opportunities. One of these is a reduction in complexity vs. size and vs. performance. It might be worthwhile to sacrifice performance in order to gain simplicity. Furthermore, it is found that in order to determine the cycle layout one must put some value on the modularity of the plant. Using the Salisbury method this could be done by increasing the incremental value of the heater surface area. The size and portability of the unit may be of little economic importance on large waterways but could be quite expensive when inland or landlocked sites are considered. One could develop an incremental heater cost for various siting conditions. It could be similar to the costing of real estate. The site on a large waterway could be compared to building a home on less developed rural land and the landlocked site would be comparative to downtown Tokyo. One could easily see the reasoning behind the difference between the size of the housing in each of these areas. However in order to reason the trade-offs in size and layout for the modularity of nuclear power plants one finds the need for analytical tools and methods like Salisbury's as above outlined.

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APPENDIX A

ORCENT-II INPUT

APPENDIX A. ORCENT-II INPUT

```
IRIS Famiani Reference with Salisbury
 1 602.6     841.219
 2 3800000.                        1.0       3968320.7
 3 300.               0.9
 4 .878      .77      220.         1.15
 5 65
 9 4.        145.       -1.22745   43.
10 3.        20.        10.        5.
11 3.        99.
12 1.        30.        25.                                      3.
13 7.        3.        4.
14 1.        408.     3.2          0.        1.                  4.06
14 2.        268.     3.37         0.        1.                  4.22
14 3.                 3.42         1.        0.
14 4.        85.      3.42         0.        1.                  3.11
14 5.        40.15    2.01         0.        1.                  2.58
14 6.        16.55    1.92         0.        1.                  2.28
14 7.        5.75     1.63         0.        1.                  1.81
15 3.        1.
16 0.
17 1.
 0
```

```
IRIS INRC8 with Salisbury
 1 602.6     841.219
 2 3800000.                                  1.0        3968320.7
 3 300.               .9
 4 .878      .77      220.         1.15
 5 65
 9 2.        225.     -1.227745    43.
10 5.        50.      30.          20.       10.          5.
11 4.        100.
12 1.        10.      25.          10.       25.
13 4.        2.                2.
14 1.        401.5    1.66         0.        1.                  6.66
14 2.        70.0     3.07         0.        1.                  8.07
14 3.        45.0     4.64         0.        1.                  9.64
14 4.        10.0     2.71         0.        1.                  7.71
15 1.        1.
16 0.
17 1.
 0
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