DESIGN STUDY
OF PORTABLE THERMOELECTRIC
NUCLEAR SYSTEMS

by

L. Chajson
A. R. DelCampo
H. B. Kellogg
R. A. Markley

and

A. A. Bishop
E. H. C. Brown
J. C. Danko

R. Eastman
L. E. Efferding
J. Locante

E. W. Ruppen
T. F. Widmer

July 1961

Declassified and Issued March 1962

Prepared for the United States Atomic Energy Commission
New York Operations Office
Contract AT(30-1)-2176, Task XIII

Approved

L. Chajson, Manager
TCR-TE Study

Westinghouse Electric Corporation
Atomic Power Department
P. O. Box 355
Pittsburgh 30, Pennsylvania

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency Thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.

ABSTRACT

Design studies have been performed and costs have been estimated for an air transportable, 10 MW(th), pressurized light water thermal circulation reactor, combined with a direct conversion thermoelectric generator and static electrical inversion equipment.

This "TCR-TE" concept appears to have potential for ultimate use as a remote unmanned power station.

Based on a modest extrapolation of present reactor technology and on assumed thermoelectric materials properties forecasted to January 1, 1963, a net ac electrical output of 315 KW is estimated, assuming the use of 80°F local water for cooling purposes. An alternate concept using 80°F air for cooling produces 271 KW, net. These electrical output figures can be improved significantly through a recommended research and development effort. The design and construction of a prototype plant is also recommended.

TABLE OF CONTENTS

	<u>Page No.</u>
LIST OF FIGURES	ix
LIST OF TABLES	xi
1. INTRODUCTION	1
1.1 Background and Purpose of Study	1
1.2 Design Requirements and Assumptions	2
2. SUMMARY	4
2.1 Performance and Description of Reference Designs	4
2.2 Possible Design Improvements and Advancements	9
2.3 Recommendations	12
3. GENERAL PLANT DESCRIPTION AND PERFORMANCE - CASE I	23
3.1 Plant Description	23
3.2 Plant Performance	24
4. REACTOR CORE - CASE I	29
4.1 Mechanical Design	29
4.2 Nuclear Design	29
4.3 Thermal and Hydraulic Characteristics	34
4.3.1 General	34
4.3.2 Pressure Drop and Flow Distribution Calculations	34
4.3.3 Hot Channel Factors	40
4.3.4 Local Boiling	41
4.3.5 Stability	41
4.3.6 Departure from Nucleate Boiling (DNB)	44
4.3.7 Comparison of Forced and Natural Convection Systems	44
5. PRIMARY SYSTEM PRESSURE VESSEL AND RELATED EQUIPMENT - CASE I	45
5.1 General	45
5.2 Reactor Vessel	47
5.3 Pressurizer	49
5.4 Control Rod Drive Mechanisms	50
5.5 Thermoelectric Heat Exchanger Assembly	52
5.6 Plant Containers	54
6. PLANT THERMAL AND HYDRAULIC PERFORMANCE - CASE I	57
6.1 General	57
6.2 Primary System Thermal and Hydraulic Performance	57
6.3 Secondary System Thermal and Hydraulic Performance	59

TABLE OF CONTENTS (Cont'd)

	<u>Page No.</u>
7. THERMOELECTRIC TUBES - CASE I	64
7.1 General.	64
7.2 Mechanical Construction of Thermoelectric Tubes. . .	64
7.2.1 Description	64
7.2.2 Fabrication	67
7.3 Thermal Characteristics of Thermoelectric Tubes. . .	69
7.4 Thermoelectric Performance Calculations.	76
8. THERMOELECTRIC GENERATOR ANALYSIS - CASE I.	80
8.1 General.	80
8.2 Results and Performance.	81
9. ELECTRICAL INVERSION SYSTEM	83
9.1 General.	83
9.2 Recommended System	83
9.3 Description of Recommended IGNITRON System	83
9.4 Alternate Systems Investigated	88
9.4.1 Transistorized Inverter	88
9.4.2 Solid State Controlled Rectifier.	88
9.5 Bases for Selection of IGNITRON System	89
10. AUXILIARY SYSTEMS - CASE I.	90
10.1 General.	90
10.2 Reactor Coolant System	90
10.3 Chemical and Volume Control System	101
10.3.1 Charging and Purification System	101
10.3.2 Water Makeup	104
10.3.3 Chemical Control	104
10.3.4 Vent and Drain System.	105
10.4 Auxiliary Coolant System	105
10.4.1 Component Cooling System	105
10.4.2 Shutdown Cooling System.	105
10.4.3 Decay Heat Removal System.	106
10.4.4 Spent Fuel Storage System	106
10.5 Safety Injection System	106
10.6 Sampling Systems	106
10.7 Secondary Coolant System	107
10.8 Waste Disposal	108
11. NUCLEAR INSTRUMENTATION - CASE I.	109
11.1 General.	109
11.2 Source Range	109
11.3 Intermediate Range	109
11.4 Power Range.	109
11.5 Radiation Monitoring	111

TABLE OF CONTENTS (Cont'd)

	<u>Page No.</u>
12. PLANT OPERATION - CASE I	113
12.1 General.	113
12.2 Cold Startup	113
12.3 Normal Operation	114
12.4 Transient Operation.	116
12.5 Shutdown	119
12.6 Refueling.	121
12.6.1 General.	121
12.6.2 Detailed Refueling Procedure	121
13. SAFETY CONSIDERATIONS - CASE I	123
13.1 Safety Analysis.	123
13.1.1 Introduction	123
13.1.2 Reactivity Accidents	124
13.1.2.1 Start-up Accident.	124
13.1.2.2 Continuous Rod Withdrawal At Power	124
13.1.2.3 Cold and Hot Water Accidents	125
13.1.3 Non-Nuclear Accidents.	125
13.1.3.1 Loss of Coolant Accidents.	125
13.1.3.2 Loss of Load Accident.	127
13.1.3.3 Loss of Coolant Flow Accident.	127
13.1.3.4 Chemical Accident.	128
13.1.3.5 Missile Accident	128
13.2 Shielding - Case I	129
13.2.1 General.	129
13.2.2 Reactor Vessel and Refueling Modules	129
13.2.3 Radioactive Auxiliaries Module	130
13.2.4 Reactor Building	130
14. GENERAL PLANT DESCRIPTION - CASE II.	131
14.1 Plant Description.	131
14.2 Plant Performance.	133
15. REACTOR CORE - CASE II	136
16. PRIMARY SYSTEM AND RELATED EQUIPMENT - CASE II	137
16.1 General.	137
16.2 Reactor Vessel	139
16.3 Pressurizer.	139
16.4 Control Rod Drive Mechanisms	140
16.5 Thermoelectric Heat Exchanger Assembly	140

TABLE OF CONTENTS (Cont'd)

	<u>Page No.</u>
17. THERMAL AND HYDRAULIC DESIGN - CASE II	142
17.1 Introduction	142
17.2 Primary System	142
17.2.1 Core Thermal and Hydraulic Design.	142
17.2.2 Primary System Pressure Drop	142
17.3 Secondary System	143
17.3.1 General.	143
17.3.2 Comparison of a Boiling and a Non-Boiling Coolant.	143
17.3.3 Pressure Drop and Heat Transfer.	146
17.3.3.1 Two Phase Pressure Drop.	146
17.3.3.2 Heat Transfer.	146
18. THERMOELECTRIC TUBES - CASE II	150
18.1 General.	150
18.2 Thermal Characteristics of Thermoelectric Tubes.	150
18.3 Thermoelectric Performance Calculations.	152
19. THERMOELECTRIC GENERATOR ANALYSIS - CASE II.	153
19.1 General	153
19.2 Performance Results.	153
20. ELECTRICAL INVERSION SYSTEM - CASE II	155
21. AUXILIARY SYSTEMS - CASE II	156
22. NUCLEAR INSTRUMENTATION - CASE II.	159
22.1 Nuclear Instruments.	159
22.2 Radiation Monitoring	159
23. PLANT OPERATION - CASE II.	160
23.1 General.	160
23.2 Cold Startup	160
23.3 Normal Operation	160
23.4 Transient Operation.	160
23.5 Shutdown	161
23.6 Refueling	161
24. SAFETY CONSIDERATIONS - CASE II.	164
24.1 Safety Analysis.	164
24.1.1 Introduction	164
24.1.2 Reactivity Accidents	164
24.1.3 Non-Nuclear Accidents.	164
24.1.3.1 Loss of Coolant Accident	164
24.1.3.2 Loss of Coolant Flow	164
24.1.3.3 Chemical and Missile Accidents	165

TABLE OF CONTENTS (Cont'd)

	<u>Page No.</u>
24.2 Shielding - Case II.	165
24.2.1 General.	165
24.2.2 Primary Shield	166
24.2.3 Secondary Shield	166
24.2.4 Fuel Handling Shield	166
24.2.5 Auxiliary Shielding.	168
NOMENCLATURE.	169
LIST OF REFERENCES.	175

LIST OF FIGURES

<u>Figure No.</u>		<u>Page No.</u>
1	TCR-TE Plant Perspective - Case I	5
2	TCR-TE Plant Layout - Case I.	6
3	TCR-TE Case I Simplified Flow Diagram	7
4	TCR-TE Case II Simplified Flow Diagram.	8
5	Construction of Thermoelectric Tube	27
6	TCR-TE Core Cross-Section	30
7	Full Fuel Element and Partial Fuel Element.	31
8	Fuel Follower and Control Rod	32
9	Core Baffle	33
10	TCR-TE Fast Flux (Average Radial)	35
11	TCR-TE Thermal Flux (Average Radial).	36
12	Identification of Fuel Assemblies in TCR-TE Core. . .	38
13	Flow Stability Vs Channel Spacing.	42
14	Reactor Power Vs. Coolant Flow.	43
15	Primary System Pressure Vessel and Related Equipment - TCR-TE Case I	46
16	TCR-TE Control Rod Drive Mechanism	51
17	TCR-TE Thermal Performance - Case I	58
18	Efficiency Vs. Secondary Flow Rate - Case I Design. .	61
19	Efficiency Vs. TE Thickness - Case I Design	62
20	Secondary Coolant Temperatures - TCR-TE Case I. . . .	63
21	TCR-TE Tube Cross-Section and Temperature Profile (Case I Reference Design)	65
22	TCR-TE Performance - Case I TE Tube Thermal Characteristics	70
23	TE Material Thickness Vs. Total Length - Case I Design	71
24	Number of Couples and Net Efficiency - Case I Design.	77
25	TE Couple Characteristics - Case I Design	78
26	Block Diagram of Recommended Inversion System	84

LIST OF FIGURES (Cont'd)

<u>Figure No.</u>		<u>Page No.</u>
27	Schematic of Recommended Inversion System	85
28	TCR-TE Auxiliary System Schematic	91
29	TCR-TE Component Cooling System	92
30	TCR-TE Proposed Secondary Coolant System - Case I . .	93
31	TCR-TE Nuclear Instrumentation System	110
32	TCR-TE Radiation Monitoring System.	112
33	TCR Response to Loss of Load.	118
34	General Plant Arrangement - Case II	132
35	Primary System and Related Equipment - Case II. . . .	138
36	Bulk Temperature of Secondary Coolant Inside TE Tubes Case II	144
37	Total Length of TE Tube Required and Secondary Pumping Power Vs. Secondary Coolant Flow Rate - Case II	145
38	Thermal Film Resistance Inside TE Tubes - Case II .	147
39	TCR-TE Tube Cross-Section and Temperature Profile (Case II Reference Design).	151
40	TCR-TE Case II - Segmented Shielding Tank	167

LIST OF TABLES

<u>Table No.</u>		<u>Page No.</u>
1	TCR-TE Design Requirements.	3
2	Summary of TCR-TE Plant Data.	14
3	TCR-TE Preliminary Package List - Case I.	25
4	Summary of TCR-TE Performance - Case I.	28
5	Comparison of TCR and TCR-TE Core Design Parameters . . .	29
6	Coolant Flow Per Fuel Assembly.	39
7	TCR-TE Hot Channel Factors.	40
8 (a)	TCR-TE Case I Design Thermal Characteristics.	72
8 (b)	Thermal Characteristics at Design Conditions.	73
9	Performance Data for Inversion System	86
10	Bill of Materials for Major Components of Inversion System	86
11	Process Instrumentation for Auxiliary Systems	94
12	TCR-TE Auxiliary System Pumps - Case I.	97
13	TCR-TE Auxiliary System Heat Exchangers - Case I.	98
14	TCR-TE Auxiliary System Tanks and Demineralizers - Case I	99
15	TCR-TE Maximum Startup Load - Case I.	115
16	TCR-TE Auxiliary Power Load During Normal Operation . . .	117
17	TCR-TE Shutdown and Erection Loads - Case I	120
18	TCR-TE Preliminary Package List - Case II	134
19	TCR-TE Auxiliary System Pumps - Case II	157
20	TCR-TE Auxiliary System Heat Exchangers - Case II	158
21	TCR-TE Auxiliary System Tanks and Demineralizers - Case II	158
22	TCR-TE Maximum Startup Load - Case II.	162
23	TCR-TE Case II Auxiliary Power Load During Normal Operation	163

1. INTRODUCTION

1.1 Background and Purpose of Study

In remote areas of the world, nuclear power plants have a clear logistic advantage over fossil fuel plants which require a continuous supply or replenishment of fuel. A 1960 study, Reference 1, shows not only a logistic advantage but also an economic justification, over the life of the plant, for small portable nuclear power plants in certain remote areas of the world. Beyond the conventional remote small nuclear power plant, the prospect of an unmanned plant promises even more logistic freedom and economic gains (Reference 2). In an unmanned plant, reliability and freedom from maintenance are of paramount importance.

As noted in Reference 2, a system which appears to have a potential for long periods of unattended operation, because of an inherently simple concept, is the thermal circulation water reactor coupled with a thermoelectric generator. In this concept, main coolant pumps and related equipment are eliminated by the use of a natural circulation primary loop. The turbine generator set with related controls and auxiliaries is eliminated and replaced by a thermoelectric heat exchanger having no moving parts to wear and no control system to fail. Once development problems, primarily in the area of the thermoelectric heat exchanger, have been solved, such a plant promises major gains in reliability and freedom from maintenance.

A subcooled light water reactor system has been chosen for the current study on the grounds that the backlog of technology in this area is far advanced over all other reactor types and thus should minimize the risk involved with the total system. In the reference designs considered, a thermal circulation reactor is combined with a thermoelectric heat exchanger (TCR-TE) in order to minimize rotating machinery. Operation in the subcooled water regime imposes practical limits on the thermoelectric material hot and cold temperatures. The relatively low thermoelectric material temperature difference results in low efficiencies compared to potential efficiencies from systems which operate at higher temperatures. However, the low temperatures (both thermoelectric material temperature difference and the plant general temperature level) are desirable from the viewpoint of good durability of thermoelectric materials and resultant plant reliability. For the ultimate goal of an unattended remote plant, such considerations are very important.

With the foregoing background information in mind, the purpose of this study has been to determine the preliminary details, including estimated costs, of two different air-transportable 10 MW(th) TCR-TE systems for remote site operation. One system utilizes local water as the heat sink while the other utilizes air. In this study, normal maintenance and normal refueling periods have been assumed. Simplification of the plants for completely unattended operation is believed ultimately possible, but is considered beyond the scope of this study.

1.2 Design Requirements and Assumptions

Certain assumptions were made at the start of the study as a result of the proposed contract wording or by AEC directive. Behind some of the assumptions was the desire to simplify calculations or eliminate new calculations in certain instances. However, such a course imposed arbitrary limitations which are reflected in the plant net output and other important parameters. The areas where improvements in these parameters are possible are covered in Section 2.2 and Appendix G. As indicated above, two cases, Case I and Case II, were studied within the framework noted in Table 1.

TABLE 1
TCR-TE DESIGN REQUIREMENTS

	<u>Case I</u>	<u>Case II</u>
Core Power (MWth)	10	10
Net Output (KWe)	Max. possible	Max. possible
TE Material	Lead telluride	Bismuth telluride
Reactor Type	Pressurized Light Water, Natural Circulation	Pressurized Light Water, Natural Circulation
Heat Sink	Lake Water (via Open Secondary Loop) at 80°F	Air (via Closed Forced-Circulation Secondary Water Loop and Tertiary Open Air Loop) at 80°F
TE Construction	Out of Core, Tubular Swaged, (Unless Plates Proven More Effective)	Out of Core, Tubular Swaged, (Unless Plates Proven More Effective)
Shielding	Portable Shield Water Tank, and Local Earth (std. radiation limits)	Integral Biologi- cal, Portable (5 Mrem/hr @ 500 ft.)
Pressurizer	Within Reactor Vessel	Within Reactor Vessel
Plant Use	Remote Location	Remote Location
Plant Transport	C-130 Aircraft	C-130 Aircraft
Inversion Type	Static	Static
Electrical Output Voltage and Type	220 V AC, 60 cycle 3 phase	220 V AC, 60 cycle 3 phase
Minimum Core Life	2 years	2 years
Size	Minimum	Minimum, Particu- larly Overall Height
Weight	Minimum	Minimum
Reliability	Maximum	Maximum
Initial Plant Installation Time	Minimum	Minimum
Maintenance	Minimum; Personnel Available	Minimum; Personnel Available
Control Rod Mechanism Location	Above Core	Above Core

2. SUMMARY

2.1 Performance and Description of Reference Designs

The concept of a direct conversion thermoelectric generator combined with a 10 MW(th), pressurized light water, thermal circulation nuclear reactor ("TCR-TE") has been studied as a possible means for meeting remote military power requirements. The results indicate that such a plant offers a significant step toward achieving the ultimate objective of an unmanned remote power station, although present efficiencies are lower and costs are higher than those of a conventional turbine-generator nuclear power plant. Figures 1 and 2 illustrate one possible TCR-TE plant arrangement.

Two design concepts have been considered. Case I requires the plant to be situated adjacent to a lake or other suitable body of water which is available as a cooling medium. Case II utilizes air as the "heat sink" and, therefore, is independent of local water requirements. Cases I and II both are designed to be transportable in a C-130 aircraft.

Each of the designs studied utilizes an integral pressurizer. Case I shielding is provided by water and earth available at the site, while Case II shielding is integral and portable. Both concepts utilize series-tubular swaged thermoelectric tube construction. The thermoelectric material is lead telluride for Case I and bismuth telluride for Case II.

Figures 3 and 4 are simplified flow diagrams of Cases I and II, respectively. As indicated on these drawings, Case I has a closed natural circulation primary water loop and an open lake-water secondary loop; Case II has a closed natural circulation primary water loop, a closed forced circulation secondary water loop, and an open tertiary air loop. The reactor auxiliaries and supporting modules, such as maintenance, sampling and waste disposal, are essentially the same for both cases. Inversion of dc to ac is accomplished by IGNITRON rectifiers for each of the concepts studied.

The net electrical output from a 10 MW(th) reactor core is 315 KW for Case I and 271 KW for Case II. Methods of improving these output figures are suggested elsewhere in the report, and are summarized in Section 2.2, which follows.

A preliminary weight and packaging analysis indicates that the basic Case I plant can be transported in twelve C-130 aircraft plane loads with the exception of core fuel assemblies, fuel followers, control rods, and refueling fuel transfer casks. The basic Case II plant requires seventeen C-130 aircraft plant loads, again with the exception of core fuel assemblies, fuel followers, control rods, and refueling fuel transfer casks. The larger number of plane loads for Case II results primarily from the use of portable shielding (6 plane loads) and the tertiary air heat exchangers.

1. REACTOR MODULE
2. REFUELING MODULE
3. SHELTER & CRANE BUILDING
4. AUXILIARIES MODULE
5. RADIOACTIVE AUX. MODULE
6. CONTROL MODULE
7. MAINTENANCE MODULE
8. SHIELD WATER COOLER
9. PURE WATER CONDENSER
10. WASTE DISPOSAL
11. EARTH SHIELD
12. LAKE
13. SAMPLING & DECONTAMINATION MODULE

**TCR-TE
PLANT PERSPECTIVE CASE I
FIGURE 1**

PLAN VIEW

SECTION A-A

TCR-TE PLANT LAYOUT - CASE I

FIGURE 2

TCR-TE CASE I
SIMPLIFIED FLOW DIAGRAM

FIGURE 3

E. D. SK. 280461 B

TCR-TE CASE II
SIMPLIFIED FLOW DIAGRAM

FIGURE 4

E. D. SK. 280462 B

Table 2, which follows all the Summary sections, presents the TCR-TE plant data for the Case I and Case II reference designs. Further details on components, systems, performance, costs, schedules, and research and development requirements are covered elsewhere in this report.

2.2 Possible Design Improvements and Advancements

The Case I and Case II reference designs are generally based on a modest extrapolation of present technology, within the "ground rules" summarized in the Introduction (Table 1, Section 1). If deviations from these ground rules are allowed or further advances in technology are considered, many methods of bettering the reference designs can be suggested. Other improvements, which require no significant changes in ground rules, suggested themselves during the latter stages of this study; unfortunately, some of these "afterthoughts" came too late to be incorporated in the reference designs. Some of the more promising ideas for improving the TCR-TE concepts are discussed in detail in Appendix G; most of these suggestions are also summarized below:

1) Reference Design Changes and Refinements

a) Further Optimization Studies on the TE Tube Design

Efficiency improvements of 5% to 10% over the reference design values appear possible with no significant increase in costs. If higher costs are allowable, considerably greater improvements in efficiency can be achieved.

b) Reduction in Thickness of the Inside (Pressure) Tube

It is likely that the thickness of the inside tube within the TE tube assembly can be reduced from 0.049 in. to 0.020 in. This change would improve the net efficiencies for either Case I or Case II by about 8%. This design modification would also either reduce the tube O.D. (decreasing the size of the overall tube bundle) or increase the I.D. (resulting in lower power requirements for pumping the secondary coolant).

c) Use of Fins or Surface Spoilers on the TE Tubes

A 13% improvement in net efficiency could be achieved by using fins to double the inside heat transfer area of the TE tubes.

d) Increase in Primary System Operating Pressure

An increase in primary system pressure from 1150 psia to 2500 psia would improve the Case I or Case II net efficiency by approximately 33%, although plant weights also would increase.

2) Improvements in Materials

a) Development of New or Improved Thermoelectric Materials

The substitution of bismuth telluride for lead telluride in the Case I reference design would increase the net efficiency by 14%. Considerable progress in the development of thermoelectric materials is foreseen in the future, offering the promise of even greater improvements in efficiency.

b) Improved Insulation Materials

The substitution of boron nitride insulation for the Al_2O_3 specified in the reference designs would improve the Case I or Case II net efficiency by about 13%.

3) Changes in Environmental Factors

a) Lower Secondary or Tertiary Coolant Temperatures

The reference design performance data were based on a "heat sink" temperature of 80°F. Considerably lower temperatures can probably be expected for extended periods of time, resulting in greater efficiencies. For example, a decrease in the temperature of the secondary coolant to 40°F would improve the Case I net efficiency by 15%.

b) Improved Water Conditions

Fouling factors lower than the assumed value of 0.0007 would result in higher efficiencies. Use of typical sea water (fouling factor = 0.0005) would improve the Case I efficiency. At start-up conditions or immediately after cleaning the tubes (zero fouling factor) an improvement of about 15% could be attained over the Case I reference design net efficiency.

4) System Simplifications and Improvements

a) Changes in Primary Coolant Purification System

Reductions in total plant weight and in auxiliary power requirements appear possible with the use of a hermetically sealed primary loop.

b) Changes in Pressurizer Design

The elimination of electrical heater controls for the pressurizer could be achieved by utilizing a constant heat input system (Reference 2). Alternatively, the complete elimination of the pressurizer and the electric heaters might be achieved, by operating at T_{sat} primary coolant conditions.

c) Simplification of Decay Heat Loop

In the Case II design, it may be possible to simplify or eliminate the decay heat system by utilizing the thermoelectric generators as the heat sink during cool-down and refueling.

d) Elimination of Nuclear Control System After Startup

As a step towards unmanned operation, the careful use of burnable poisons combined with the core negative temperature coefficient may make it possible to eliminate the nuclear control system.

e) Reduction of Power Requirements for Case II Cooling Fans

It appears that about 20 KWe could be saved by substituting centrifugal blowers for the propeller fans specified in the Case II reference design.

5) Advanced System Concepts

a) In-Core Thermoelectric Systems

Studies completed at the Westinghouse Atomic Power Department indicate that major improvements in overall plant efficiency could be achieved with in-core thermoelectric systems, by taking advantage of the large thermal gradients within the core. The relative simplicity of this concept may also permit significant reductions in plant weight.

b) High Temperature Reactor Systems

The use of liquid-metal cooled and gas cooled reactor systems may make it possible to achieve considerably greater efficiencies because larger thermal gradients can be obtained across the thermoelectric material. For example, net efficiencies of 7 to 12% are obtainable with primary coolant temperatures of 1000°F to 1200°F, utilizing lead telluride TE material.

Of the above items, Numbers 1, 2, 3 and 4 suggest methods of improving the specific TCR-TE design concepts studied in detail in this report. Some of these ideas can be incorporated with little additional effort, while others will require more work before technical and economic feasibility can be established. Studies in all of these areas are recommended.

Item 5, above, suggests two thermoelectric system concepts which differ in many respects from the Case I and Case II reference designs. Both of these systems appear to offer significant improvements in efficiency. However, technical and economic studies similar to those carried out in this report must be performed to permit a valid comparison of these new concepts against each other and against the TCR-TE reference designs.

2.3 Recommendations

Areas of investigation requiring additional effort are discussed in detail throughout this report, particularly in Appendices A and G. The many detailed suggestions for further study can be summarized within the following major recommendations:

- 1) Studies should be continued on the possible design improvements and advancements presented briefly in Section 2.2. Technical and economic evaluations of an in-core thermoelectric plant and a high-temperature (liquid-metal or gas cooled) thermoelectric reactor system are particularly recommended.
- 2) A 10 MW(th) prototype plant based on the TCR-TE Case I concept described in this report should be designed and built. The cost of such a plant is estimated (Appendix B) at about 4.2 million dollars, including the first core but excluding fixed fee. The cost of the pre-construction research and development program (Appendix A, Section 2) believed necessary in order to build this plant is approximately 1.2 million dollars, exclusive of fixed fee.
- 3) Concurrently with the design and construction of the prototype plant, a research and development program aimed at optimized future plants should also be undertaken. A major portion of this additional research and development work would be carried out in the TCR-TE prototype plant. The estimated costs of all recommended post-construction research and development programs (Appendix A, Sections 3, 4 and 5) total approximately 2.3 million dollars, excluding fixed fees.
- 4) Plans should be initiated to design and build "production model" plants based on the TCR-TE Case I and/or Case II concepts.

Assuming firm price quotations would be requested, the estimated costs (Appendix B) of "production model" plants, subsequent to the first one, would be about 2.7 million dollars for Case I and 3.1 million dollars for Case II. The additional cost of the core is estimated as \$115,000, for either design concept.

The Case I and Case II reference designs presented in this report represent thermoelectric and nuclear technology levels which are either current or can be attained with relatively-modest expenditures of research and development funds. It is recognized that, at the present time, TCR-TE plants will be more expensive than a conventional nuclear turbine-generator system of a similar rating. However, the TCR-TE concepts, combined with some of the improvements suggested in Section 2.2, are believed to offer excellent potential for achieving the ultimate goal of an unmanned remote power station.

As discussed previously, simplification and optimization studies and the evaluation of alternate concepts can be continued to good advantage. However, the real worth of the TCR-TE plant, or any promising new concept, can only be determined through the actual construction of a prototype system. The design, construction and operation of a prototype plant will make it possible to identify problem areas and to focus the necessary research efforts on the areas where the greatest gains in useful knowledge can be realized.

TABLE 2

SUMMARY OF TCR-TE PLANT DATA

	<u>Case I</u>	<u>Case II</u>
<u>A. SYSTEMS CHARACTERISTICS</u>		
<u>1. Power Plant General Cycle Data</u>		
Nuclear Reactor Type	Pressurized-Thermal Circulation	Pressurized-Thermal Circulation
Primary Coolant	Light Water	Light Water
Reactor Moderator	Light Water	Light Water
Reactor System Pressure	1,150 psia	1,150 psia
Reactor Thermal Output	10.0 MW	10.0 MW
Plant Gross Electrical Efficiency	4.07%	3.97%
Gross Plant Power Output	407 KWe	397 KWe
Losses (Normal Operation)		
Auxiliary Power	18.2 KWe	18.2 KWe
Hotel Load-Reactor System	7.8 KWe	7.8 KWe
Secondary Pumping Power	25.0 KWe	10.0 KWe
Tertiary Fan Power	----	50.0 KWe
Inversion Losses	41.0 KWe	40.0 KWe
Total Losses	92 KWe	126 KWe
Net Plant Power Output	315 KWe	271 KWe
Plant Net Electrical Efficiency	3.15%	2.71%
Net Voltage	220 Volts	220 Volts
Net Current	1430 amps	1230 amps
<u>2. Primary System Characteristics</u>		
Coolant Flow Rate	515,000 lb/hr	515,000 lb/hr
Number of Coolant Passes Through Core	1	1
Coolant Bulk Outlet Temp.	552°F (10° sub-cooled)	552°F (10° sub-cooled)

	<u>Case I</u>	<u>Case II</u>
Coolant Inlet Temperature	498°F	498°F
Coolant Average Temperature	526°F	526°F
Pressure Drop (External to Core)	29.9 psf	33.1 psf
Pressure Drop (Reactor Core)	5.4 psf	5.4 psf
Total System Pressure Drop	35.3 psf	38.5 psf
Thermal Driving Head (Core to Heat Exchanger Centerlines)	10.5 ft	11.5 ft
Coolant Velocity in Core Along Fuel Plates	1.7 ft/sec	1.7 ft/sec

3. Secondary System Characteristics

Secondary Pressure	Ambient plus pumping head	Ambient plus pumping head
Secondary Coolant Source	Lake water	Intermediate sub-cooled water
Secondary Pumping Power	25 KWe	10 KWe
Secondary Coolant Flow Rate	500,000 lb/hr	1,060,000 lb/hr
Secondary Coolant Average Temperature	112°F	211°F
Secondary Coolant Inlet Temperature	80°F	195°F
Secondary Coolant Exit Temp.	144°F	227°F

4. Tertiary System Characteristics

Type	----	Induced Air
Pressure	----	Ambient
Air Flow Rate	----	84,000 scfm/unit
Total Fan Power	----	50 KWe
Air Inlet Temperature	----	80°F
Air Exit Temperature	----	178°F
Air Average Temperature	----	129°F
Heat Exchanger Air Side ΔP	----	1.23 psf
Type Fans	----	7 ft dia. propeller (50% eff)

Case ICase IIB. COMPONENTS CHARACTERISTICS1. Reactor Core Data

Fuel Type	UO ₂ , stainless steel B ₄ C Cermet	UO ₂ , stainless steel B ₄ C Cermet
Enrichment, New Fuel	93.07%	93.07%
Enrichment, Depleted Fuel	90.33%	90.33%
U-235 Loading (initial)	33.7 kg	33.7 kg
U-235 Loading (final)	22.7 kg	22.7 kg
Fuel Geometry	Flat plates	Flat plates
Cladding Material	Stainless steel	Stainless steel
Cladding Thickness	0.005 in.	0.005 in.
Meat Material	UO ₂ (28.59%), B ₄ C (0.31%), S.S. (71.10%)	UO ₂ (28.59%), B ₄ C (0.31%), S.S. (71.10%)
Meat Thickness	0.040 in.	0.040 in.
Plate Separation	0.250 in.	0.250 in.
Number of Fuel Assemblies (Full, Partial and Followers)	29	29
Lifetime (at 95% load factor)	2 + years	2 + years
Core Diameter (equivalent)	22.1 in.	22.1 in.
Active Core Length	27 in.	27 in.
Length to Diameter Ratio	1.22	1.22
Total Active Core Volume	1.70 x 10 ⁵ cm ³	1.70 x 10 ⁵ cm ³
Water/Metal Ratio	3.65	3.65
Average Thermal Neutron Flux	1 x 10 ¹³ n/cm ² -sec	1 x 10 ¹³ n/cm ² -sec
Maximum Center of Fuel Temp.	617°F	617°F
Average Heat Flux (followers 1/3 inserted)	86,800 BTU/hr-ft ²	86,800 BTU/hr-ft ²
Peak/Average Heat Flux (F _q)	3.46	3.46
Peak/Average Film Drop (F _e)	3.12	3.12
Peak/Average Enthalpy Rise (F _{ΔH})	1.78	1.78

	<u>Case I</u>	<u>Case II</u>
Total Active Heat Transfer Surface Area	428 ft ²	428 ft ²
Bettis Burnout Flux Correlation	1.24 x 10 ⁶ BTU/hr-ft ²	1.24 x 10 ⁶ BTU/hr-ft ²
"DNB" Safety Factor	4.6	4.6
Power Density (Total Active Core Volume)	59.1 watts/cc	59.1 watts/cc
Power Density (Core Coolant Volume)	75.3 watts/cc	75.3 watts/cc
Average Steam Quality (Core Exit)	0%	0%
Hot Channel Steam Quality	5.7%	5.7%
Flow Redistribution (Favorable)	130%	130%
<u>2. Reactivity Control System</u>		
Number of Control Rods	5	5
Core Entry of Control Rods	Top	Top
Control Rod Drive Mechanism Type	3 coil, latch-type magnetic jack	3 coil, latch-type magnetic jack
Reactor Vessel Entry of Control Rod Mechanisms	Top	Top
Control Rod Normal Speed (Exit Core and Removal)	4 in./min	4 in./min
Control Rod Stroke Length	27 in.	27 in.
Other Control Systems	Emergency boron injection system	Emergency boron injection system
Control Rod Material	Eu ₂ O ₃ - S.S. Cermet	Eu ₂ O ₃ - S.S. Cermet
Control Rod Follower Material	Movable fuel assy.	Movable fuel assy.
Reactivity Allowances, % Δk/k		
Xe (equilibrium)	1.5	1.5
Xe (maximum after shutdown)	2.5	2.5
Sm (equilibrium)	0.5	0.5
Temperature (cold to hot)	5.4	5.4

	<u>Case I</u>	<u>Case II</u>
Fission Product Poisoning and Burnup	2.0	2.0
Steam Voids	0.14	0.14
Initial Shutdown Margin	10.1%	10.1%
Cold Temperature Coefficient	$-0.26 \times 10^{-4}/^{\circ}\text{F}$	$-0.26 \times 10^{-4}/^{\circ}\text{F}$
Hot Temperature Coefficient	$-3.0 \times 10^{-4}/^{\circ}\text{F}$	$-3.0 \times 10^{-4}/^{\circ}\text{F}$
3. <u>Reactor Vessel</u>		
Operating Pressure	1150 psia	1150 psia
Design Pressure	1500 psia	1500 psia
Test Pressure (cold)	2250 psia	2250 psia
Material of Construction (Cylindrical Section)		
Lower	Type 316 S.S.	Type 316 S.S.
Upper	Type 302, Grade B or U.S.S. HY-80, with 0.1 in. Type 304 stainless steel clad	Type 302, Grade B or U.S.S. HY-80, with 0.1 in. Type 304 stainless steel clad
Operating Temperature	500°F	500°F
Design Temperature	600°F	600°F
Inside Diameter (Core Level)	39 in.	39 in.
Wall Thickness (Core Level)	1-7/8 in.	1-7/8 in.
Flange Diameter	54 in.	51 in.
Weight	12,200 lb.	18,100 lb.
Overall Length (bottom of vessel to top of flange)	9 ft. 11 in.	10 ft. 2 in.
4. <u>Primary to Secondary Heat Exchanger</u>		
Number Required	1	4
Type of Construction	Integral, U-tube	External, Straight- through
Shell Construction Material	U.S.S. HY-80	U.S.S. HY-80

	<u>Case I</u>	<u>Case II</u>
Weight		
Vessel Shell	12,662 lb	11,200 lb. (for 4)
TE Tubing	12,225 lb	14,000 lb. (for 4)
Brackets & Flow Baffle	<u>550 lb</u>	
Total	25,437 lb	
Outside Diameter (TE Tube Bundle)	----	30.5 in.
Overall Log Mean ΔT	414°F	315°F
Heat Transfer Surface Area (O.D.)	1280 ft ²	1690 ft ²
Number of Tubes (Total)	640	1520
TE Length per Tube	9.0 ft	5.0 ft
Tube Row Spacing	0.975 in.	1.25 in.
Design Heat Load	35.6 x 10 ⁶ BTU/hr	35.6 x 10 ⁶ BTU/hr
5. <u>Heat Exchanger Tubes (Thermoelectric)</u>		
Tube O.D.	0.850 in.	0.850 in.
Tube I.D.	0.272 in.	0.272 in.
Inner Tube Material	Stainless steel	Stainless steel
Insulation Material	Supramica, Mica and Al ₂ O ₃	Supramica, Mica and Al ₂ O ₃
Cold Conductor Material	Fe-Cu	Fe-Cu
Hot Conductor Material	Fe-Cu	Fe-Cu
TE Material (n-type)	Doped Lead Telluride	Doped Bismuth Telluride
TE Material (p-type)	Doped Lead Telluride	Doped Bismuth Telluride
Eff. Length of Tubes	5750 ft.	7600 ft.
TE Length per Tube	9.0 ft.	5.0 ft.
Thickness of TE Material	0.120 in.	0.120 in.
Length of TE Couple (Axial Direction)	0.820 in.	0.820 in.
TE Tube Construction	Swaged Series-Tubular	Swaged Series-Tubular
Tube Heat Flux (O.D.)	24,200 BTU/hr-ft ²	20,100 BTU/hr-ft ² -°F

	<u>Case I</u>	<u>Case II</u>
Tube Overall Coefficient of Heat Transfer (U_o)	58.4 BTU/hr-ft ² -°F	63.8 BTU/hr-ft ² -°F
Primary Side Fouling Factor	0.0002 hr-ft ² -°F/BTU	0.0002 hr-ft ² -°F/BTU
Secondary Side Fouling Factor	0.0007 hr-ft ² -°F/BTU	0.0002 hr-ft ² -°F/BTU
Primary Side Heat Transfer Coefficient	770 BTU/hr-ft ² -°F	1060 BTU/hr-ft ² -°F
Secondary Side Heat Transfer Coefficient	3000 BTU/hr-ft ² -°F	3100 BTU/hr-ft ² -°F
Average TE Couple <u>Material</u> Figure of Merit	$1.85 \times 10^{-3} (^\circ\text{C})^{-1}$	$2.20 \times 10^{-3} (^\circ\text{C})^{-1}$
Average TE Couple <u>Design</u> Figure of Merit	$1.745 \times 10^{-3} (^\circ\text{C})^{-1}$	$2.05 \times 10^{-3} (^\circ\text{C})^{-1}$
Average TE Couple Electrical Resistance	203×10^{-6} ohms	177×10^{-6} ohms
Average TE Couple Seebeck Coefficient	462×10^{-6} Volts/°C	450×10^{-6} Volts/°C
Average TE Hot Side Temp.	470.1°F	459°F
Average TE Cold Side Temp.	236°F	256°F
ΔT , Thermoelectric Material	234.1°F	203°F
Thermoelectric Efficiency Factor, e_{TC}	16.1%	18.0%
$M = \frac{R_L}{R_c}$	1.336	1.39
Total Electrical Power Generated Per Couple	7.6 watts	6.2 watts
Gross Electrical Power Produced Per Couple	4.88 watts	3.6 watts
Couple emf Generated	0.06015 Volts	0.05073 Volts
Couple Current	126 amps	122 amps
Number of TE Couples Required	83,300	111,000

Case ICase II6. Pressurizer

Type	Integral with Reactor Vessel	Integral with Reactor Vessel
Total Volume	37 ft ³	41.5 ft ³
Normal Steam Volume	28 ft ³	32.5 ft ³
Outside Diameter (Center Section)	51.25 in.	51.25 in.
Length	6 ft.	6 ft. 4 in.
Heat Capacity	46 KW installed	46 KW installed
Number of Heater Assemblies	40	40

7. Auxiliary Systems

Maximum Coolant Makeup Rate	4 gpm	4 gpm
Maximum Purification Rate	2 gpm	2 gpm
Auxiliary Power Load-Normal Operation	91.7 KW	126 KW

8. Generator Characteristics

Closed Circuit Voltage (full power)	250 V dc	270 V dc
Open Circuit Voltage	500 V dc	540 V dc
Current Flow	1630 amps	1470 amps
Number of Parallel Hookups	13	12
Thermoelectric Material Specific Gross Power	0.202 watts/gm.	0.17 watts/gm.

9. Inversion and Regulation Characteristics

Type of Inversion System	IGNITRON	IGNITRON
Inversion Efficiency	90%	90%
Type of Voltage Regulation	Heat dissipation	Heat dissipation
Weight	15,000 lb	15,000 lb

	<u>Case I</u>	<u>Case II</u>
10. <u>Secondary to Tertiary Heat Exchanger</u>		
Type	----	Air Blast Coolers (PM-1 Type)
Units Required	----	4
Tubing	----	17 BWG 1 in. O.D. 3 in. pitch, 11 fins/ in., 1.886 in. O.D., 0.015 in. thickness
Fin Surface Area	----	3.76 ft ² /linear ft
Tube Configuration	----	8 rows x 31 columns 16 ft active length, U-tube
Air Side Heat Transfer Film Coefficient		11.7 BTU/hr-ft ² -°F
Fin Efficiency	----	92%
Tube Overall Heat Transfer Coefficient	----	8.3 BTU/hr-ft ² -°F
Total Air Side Heat Transfer Area	----	15,000 ft ² /Unit
Secondary Side Heat Transfer Coefficient	----	735 BTU/hr-ft ² -°F
ΔT_{LMTD}	----	77°F
Size	----	8 ft 6 in. x 8 ft 6 in. x 17 ft/ea.

3. GENERAL PLANT DESCRIPTION AND PERFORMANCE - CASE I

3.1 Plant Description

The TCR-TE Case I plant is a 10 MW(th) air transportable direct conversion thermoelectric-nuclear reactor system utilizing direct lake water cooling for the thermoelectric tube cold side. The plant electrical output is 315 KW. Figures 1 and 2 illustrate a general plant arrangement for a remote U.S.A. location. From these drawings, it can be seen that there are two main modules. One module consists of a 28-1/2 ft. high, 8-1/2 ft. diameter, shield water tank containing the integral reactor vessel - thermoelectric heat exchanger - pressurizer. Adjacent to this module is a second module, of similar dimensions, used for refueling and spent fuel storage. Grouped around the two modules are the supporting systems such as inversion equipment, reactor auxiliaries, controls, standby power unit, etc. The system utilizes no turbine generator equipment - all electrical output being generated by the thermoelectric heat exchanger.

The pressure vessel located in the shielding tank module consists of three main sections bolted together - a lower reactor vessel section containing the core, a middle heat exchanger section containing the thermoelectric tubes, and a top section consisting of an integral pressurizer and magnetically operated control rod drive mechanisms. Details of the pressure vessel design are covered in Section 5 of this report.

Adjacent to the shielding tank module and connected by a common canal is the refueling tank module. Racks for storing spent fuel elements are located at the bottom of this tank.

A reactor building encloses the shielding tank, the refueling tank and an adjacent temporary storage area. Within this building, the 20 ton traveling crane used for plant erection and refueling is located. In order to keep radiation in the building to reasonable levels during plant operation, a dish-shaped cover, containing 20 inches of water, is provided at the top of each of the two water tanks. The shielded radioactive auxiliaries module is located underground adjacent to the temporary storage area. This module contains a regenerative heat exchanger, a non-regenerative heat exchanger, a demineralizer, the shield water demineralizer and pump, and related piping, valves and instrumentation.

The reactor auxiliaries module is located at ground level adjacent to the shielding and refueling tanks and contains the charging pumps, centrifugal pumps, liquid storage tanks, decay heat exchanger, secondary loop filters, pumps and related piping, valves and instrumentation.

The shield water auxiliary air blast cooler module is located adjacent to the reactor auxiliaries module. This module contains four water to air heat exchangers whose major function is cooling the shield water.

A water tank and transfer pump are provided for storage and supply of water during changes of water levels in the shielding and refueling tanks during refueling. Depending upon site water conditions, the storage tank may not be required. The tank is located below ground level adjacent to the refueling tank.

A plant control module, located a short distance from the reactor building, contains the display and control consoles for all primary and secondary reactor systems, thermoelectric electrical output, inversion equipment, standby power, vital power control, and alarms. This module also contains the inversion and voltage regulating equipment, including IGNITRONS, transformers, breakers, filters, resistor bank, resistor bank tank, air cooled condenser and pure water storage tank and transfer pump.

The standby and maintenance package contains the auxiliary 50 KW diesel generator, batteries, small machine shop equipment for normal maintenance work, and hand tools, etc.

The decontamination and sampling module is located adjacent to the standby and maintenance equipment. It contains personnel decontamination equipment and a sampling cubicle with related analytical equipment.

Finally, a waste disposal module, located underground and remotely from the remaining modules, is provided for processing liquid, gaseous and solid radioactive wastes. The exact location of this module will depend upon local terrain conditions.

It is estimated that the complete Case I plant can be shipped in twelve C-130 aircraft plane loads as shown on Table 3. Core fuel assemblies, followers, control rods and fuel transfer casks have been omitted from the summary of initial plant weights, although they are included in the cost estimates given elsewhere in this report.

3.2 Plant Performance

Selected performance data for the TCR-TE, Case I, plant are summarized in Table 4. In this table, three different secondary water fouling factors are considered for design evaluation purposes, while the heat flow rate and other parameters (except the length of TE tubing) are held constant. A factor of .0007 has been chosen for the reference design, as noted in the starred (*) column. Detailed performance data for this reference design are presented in the Summary of TCR-TE Plant Data, Table 2 of Section 2.

TABLE 3

TCR-TE PRELIMINARY PACKAGE LIST - CASE I

(Weights include skids and weatherproof covers but do not include core fuel assemblies, fuel followers, control rods, and refueling transfer casks.)

<u>Plane Load No.</u>	<u>Description</u>	<u>Est. Size</u>	<u>Est. Weight</u>
1.	Thermoelectric Heat Exchanger	6' x 6' x 11'	30,000 lb.
2.	Reactor Vessel and Lower Shield Water Tank	8'6" x 8'6" x 11'	28,900 lb.
3.	Pressurizer, Internals and Tank Covers	8'6" x 8'6" x 18'	29,800 lb.
4.	Upper Shield Water Tank and Shielding	8'6" x 8'6" x 19'	29,100 lb.
5.	Refueling Tank and Shielding	8'6" x 8'6" x 30'	30,000 lb.
6.	Crane and Shielding	8'6" x 8'6" x 15'	30,000 lb.
7.	Plant Control and Inversion Equipment	8'6" x 8'6" x 30'	29,600 lb.
8.	Auxiliaries, Radioactive Auxiliaries and Pure Water Condenser	8' x 8' x 25'	29,900 lb.
9.	Maintenance, Tanks, and Misc.	8'6" x 8'6" x 30'	29,400 lb.
10.	Shield Water Cooler and Waste Disposal	8' x 8' x 20'	30,000 lb.
11.	Decontamination and Sampling	8'6" x 8'6" x 30'	18,100 lb.
12.	Refueling Tools and Water Storage	8'6" x 8'6" x 30'	14,300 lb.
Total Weight (including shipping containers but excluding core fuel assemblies, fuel followers, control rods, and refueling transfer casks)			291,000 lb.

The reactor primary system pressure and the design assumptions about the secondary coolant are based on the requirements and assumptions noted in the Introduction, Section 1.2. The secondary coolant flow rate of 500,000 lbs/hr provides approximately optimum plant performance. The thermoelectric material wall thickness of 0.120" and the couple length of 0.82" were selected as a reasonable compromise between maximum efficiency, minimum material utilization and ease of fabrication. The secondary coolant fouling factor was varied between zero (clean) and .0011 hr-ft²-°F/BTU to illustrate its significant effect on system performance. Since no exact site location has been prescribed for the TCR-TE installation, the value of this factor cannot be set at this time. However, fouling factors of the magnitude used in this study require either high grade coolant water or frequent heat exchanger tube cleaning. A fouling factor of .0007 hr-ft²F/BTU was chosen for the reference design, since this is believed to be a representative value.

The thermoelectric material specified for the Case I design is "n" and "p" doped lead telluride. Its performance has been forecasted to January 1, 1963, when a Z_{ave} value of $1.85 \times 10^{-3} (^\circ\text{C})^{-1}$ is predicted. With this thermoelectric material combined into the heat exchanger tube design shown in Figure 5 ($t_{TE} = 0.120"$ and $L_{CO} = 0.82"$), an optimum thermoelectric material conversion efficiency factor, e_{TC} , of 16.1% results, as described in Appendix F.

The plant net electrical efficiency for the Case I reference design is predicted to be 3.15%. The gross thermoelectric generator electrical efficiency is 4.07% which is equivalent to an electrical output of 407 KW from a thermal circulation reactor with a 10 MW(th) core rating. This gross electrical output is produced as 250 Volt, 1630 amp dc power. The estimated auxiliary power requirements and inversion losses which form the basis for these efficiencies are itemized in Table 4 and discussed in greater detail in Section 12.

The total length of heat exchanger tubing containing thermoelectric material is 5750 ft. This length of tubing requires 83,300 TE couples having a length of 0.82 inches. Shorter couples slightly increase the system efficiency, but the required number of couples (i.e., cost) also increases greatly. Thus, the compromise length of 0.82" was selected for the reference design.

CONSTRUCTION OF THERMOELECTRIC TUBE

FIGURE 5

TABLE 4

SUMMARY OF TCR-TE PERFORMANCE - CASE I

Secondary Fouling Factor - r_i	$(\frac{\text{hr} \cdot \text{ft}^2 \cdot ^\circ\text{F}}{\text{BTU}})$	0 (clean)	* .0007	.0011
Core Rating	MW(th)	10	10	10
Thermoelectric Generator Output	KWe	460	407	377
Losses (Normal Operation)				
Auxiliary Power - Reactor	KWe	18.2	18.2	18.2
Hotel Load - Reactor System	KWe	7.8	7.8	7.8
Secondary Loop Pumps	KWe	25	25	25
Inversion (90% Effic.)	KWe	<u>46</u>	<u>41</u>	<u>38</u>
Total Losses		97	92	89
Net Plant Output	KWe	363	315	288
Gross Plant Efficiency - e_g	%	4.6	4.1	3.8
Net Plant Efficiency - e_{net}	%	3.63	3.15	2.88
Primary Coolant Flow Rate	lb/hr	515,000	515,000	515,000
Secondary Coolant Flow Rate	lb/hr	500,000	500,000	500,000
Primary System Pressure	psia	1150	1150	1150
Secondary Loop Pressure	psia	$\approx$ Ambient	$\approx$ Ambient	$\approx$ Ambient
Primary Cooling T_{in}	$^\circ\text{F}$	498	498	498
Secondary Coolant T_{in}	$^\circ\text{F}$	80	80	80
TE Material Thickness - t_{TE}	in.	0.120	0.120	0.120
Thermoelectric Couple Length	in.	0.820	0.820	0.820
Total TE Tubing Length				
Required (4% Margin) - $\bar{L}$	ft.	4920	5750	5920

* Reference Design - Case I

4. REACTOR CORE - CASE I

4.1 Mechanical Design

The TCR-TE core utilizes flat plate fuel elements containing a UO_2 , stainless steel, and B_4C cermet and is based on SM-1 (APPR) core designs. Fuel enrichment is 93% at the beginning of life.

Control rods are open rectangular flux traps containing a Eu_2O_3 stainless steel cermet as the absorber material. Fuel followers are located below the control rods. Figure 6 is a cross-section schematic of the core.

There are sixteen full-sized fuel elements, each containing thirteen fuel plates, and eight partial-sized fuel elements, each containing five fuel plates (See Figure 7). The fuel cermet is .040 inch thick and 27 inches long, clad with .005 inch stainless steel. The water channel spacing between fuel plates is 0.250 inch. The initial core loading is 33.7 Kg U-235.

Attached to each of the five control rods is a fuel follower assembly. As shown in Figure 8, each fuel follower is similar to the full fuel element except that it contains twelve fuel plates instead of thirteen.

The core baffle, surrounding the core, is made of a number of one-eighth inch thick flat stainless steel plates as shown in Figure 9. The upper and lower core support grids consist of three-eighths inch thick flat stainless steel plates assembled into an "egg-crate" form.

4.2 Nuclear Design

Early in the TCR-TE Study, it was determined that the core utilized for the TCR (Reference 3) would be used with as few changes as possible in order to eliminate extensive nuclear calculations from the scope of the work. Accordingly, no nuclear calculations have been made. However, as shown in Table 5, minor changes have been made over values used in the TCR study.

TABLE 5
COMPARISON OF TCR AND TCR-TE CORE DESIGN PARAMETERS

<u>Item</u>	<u>TCR</u>	<u>TCR-TE</u>
Reactor Core Power (MW-th)	9.03	10
Average Core Heat Flux (followers 1/3 inserted) (BTU/hr-ft^2)	78,300	86,800
Reactor Main Coolant Flow Rate (lb/hr)	480,000	515,000
Core Lifetime (Years)	3+ (80% load factor)	2+ (95% load factor)

TCR-TE CORE CROSS-SECTION

FIGURE 6

FULL FUEL ELEMENT & PARTIAL FUEL ELEMENT

FIGURE 7

FUEL FOLLOWER & CONTROL ROD

FIGURE 8

Fast flux and thermal flux plots as a function of radial distance from the core are shown in Figures 10 and 11. These curves are based on work completed under the TCR study but are applicable, to a close approximation, to the TCR-TE study.

Before a final design is formulated, nuclear design work is considered necessary as a part of the engineering program leading to the prototype design to determine core lifetime, shutdown margin, and other important parameters. As discussed in Appendix A, research and development programs in this area are also recommended.

4.3 Thermal and Hydraulic Characteristics

4.3.1 General

The thermal and hydraulic performance of a water cooled nuclear reactor is evaluated by determining the flow rate through the various hydraulic regions of the reactor. The core is one of the major areas requiring thermal and hydraulic evaluation. The heat generated in the core must be safely removed and then transferred to a cooling component. In the TCR-TE system, the heat from the core is transferred to the thermoelectric heat exchanger tubes. The resulting temperature gradient across these tubes generates the electrical power according to the principles of thermoelectricity.

In a natural circulation reactor there is a tendency for flow to follow power. For the range of conditions under consideration, this tendency is favorable, (i.e., the regions having high power density have high flow, resulting in a self-compensating effect). Because of the radial power variation in the core, there is no "average" fuel assembly.

In order to analyze a natural circulation core, two flow redistribution calculations must be performed: the first to obtain the flow rate in the fuel assemblies; the second to obtain the flow rate in the hot channel(s). The hot spot and hot channel concepts are used as the basis for the thermal design. The thermal and hydraulic characteristics are tabulated in the Summary of TCR-TE Plant Data, Table 2, Section 2.

4.3.2 Pressure Drop and Flow Distribution Calculations

The coolant flow rate in a natural circulation system is determined by balancing the sum of all pressure drops against the available thermal driving force. The thermal driving force, which is equal to the unit difference in densities of the hot and cold fluids integrated over the height of the coolant flow loop, is equal

TCR-TE FAST FLUX (AVERAGE RADIAL)

FIGURE 10

DO. NO. 201100 0

TCR-TE THERMAL FLUX (AVERAGE RADIAL)

FIGURE 11

to the sum of the pressure drops around the loop. In these particular TCR-TE applications, the pressure drop across the TE tubes is the largest pressure drop in the system. The drop through the core, although important, is smaller.

The pressure drops through the system, exclusive of the core and TE tubes, have been calculated by the usual methods for friction and acceleration with non-isothermal flow. To determine the core pressure drop it is necessary to determine the coolant flow distribution across the core. The flow in each region of the core is assumed to be controlled by the heat input to that region and the pressure drop. The pressure drop is calculated by determining the coolant velocity and heat transfer conditions; i.e., non-boiling, local boiling or bulk boiling.

To use this method, it is necessary to make assumptions about the heat flux distribution. The power distribution, for the case with the control rod fuel-bearing followers fully inserted into the core, is assumed to follow a chopped J_0 Bessel function radially and a chopped cosine function axially.

For purposes of thermal and hydraulic calculations, five types of fixed fuel assemblies and two types of fuel follower assemblies in the core have been used, as shown in Figure 12. Each assembly is lettered according to its location relative to the center.

A graphical solution for the pressure drops and flow distribution with the followers completely inserted has been obtained by following the procedure outlined in Appendix H.

The flow distribution and pressure drop have also been calculated for the condition with the control rod followers inserted one-third of the way into the core; that is, with the control rods inserted two-thirds. This is the deepest control rod insertion during power operation. The flow rates determined for each region, at each follower position, are shown in Table 6. The pressure drop across the core for partially inserted followers has been calculated by the same methods as for the case with the control rods fully inserted. (See Appendix H).

A pressure drop across the TCR-TE reactor core of 5.3 psf was calculated for a primary flow rate of 515,000 lbs/hr, a water channel spacing of 0.250 in. and a core length of 27 inches. Further descriptive data on the core are given in the Summary of TCR-TE Plant Data, Table 2, Section 2.

IDENTIFICATION OF FUEL ASSEMBLIES
IN TCR-TE CORE

FIGURE 12
-38-

ED. SK. 288807 C

TABLE 6
COOLANT FLOW PER FUEL ASSEMBLY

<u>Assembly</u>	<u>Flow per Assembly, lb/hr</u>		<u>Energy Release per Assembly</u>	
	<u>Follower</u> <u>Inserted</u> <u>9 inches</u>	<u>Follower</u> <u>Fully</u> <u>Inserted</u>	<u>Btu/hr 10⁻⁶</u> <u>9 inches</u>	<u>27 inches</u>
A*	14,720	23,030	0.69	1.71
B	25,800	24,240	2.13	1.86
C	24,400	22,080	1.86	1.63
D*	11,710	15,680	0.42	1.07
E	18,300	17,690	1.2	1.06
F	7,810	7,260	0.33	0.29
G	7,860	7,270	0.34	0.29

* Control rod assembly

4.3.3 Hot Channel Factors

The three hot channel factors used in the design of the TCR-TE are $F_{\Delta H}^T$, the enthalpy rise factor; F_q^T , the heat flux hot channel factor and F_{θ}^T , the coolant film temperature drop hot channel factor.

Each factor is the product of nuclear and engineering sub-factors. The engineering sub-factors include the effect of fuel rod characteristics and flow variations on the performance of the hot channel compared to the average channel. The nuclear sub-factors include the effect of radial, axial and peaking variations of the neutron flux in the reactor. The standard approach is taken that the worst combination of these factors can occur at a spot in the reactor. This spot is commonly called the "hot spot".

In a natural circulation reactor the flow redistribution is favorable. Thus, there is more flow through the hot channel than in the average channel. The ratio of the flow in the hot fuel to that in the average fuel assembly is approximately 1.30.

The values of the hot channel factors used in this study are given in Table 7 .

TABLE 7

TCR-TE HOT CHANNEL FACTORS *

<u>Engineering Factors, F^E</u>	$F_{\Delta H}$	F_q	F_{θ}
Fuel Rod Characteristics	1.18	1.13	1.25
Effective Flow Distribution	0.8	--	0.8
<u>Nuclear Factors, F^N</u>			
Radial	1.55	1.55	1.55
Peaking	1.22	1.22	1.22
Axial	--	1.62	1.62
<u>Total Factors, F^T</u>	1.78	3.46	3.06

The coolant film temperature drop hot channel factor provides an indication of whether local boiling exists in the core.

$$* F^T = F^N \times F^E$$

4.3.4 Local Boiling

Although the coolant is not in bulk boiling as it leaves the core there can be substantial local boiling in the TCR-TE core. There is limited ($\approx 6\%$) bulk boiling in the hot channel. The Jens and Lottes correlation is used to determine when and where local boiling exists. For stability and transient analysis, it is important that the void fraction or local steam volume which is present during local boiling be accurately known. The methods reported in WAPD-AD-TH-556 (Reference 4) are used to predict the local boiling steam voids. This approach is semi-empirical and is based on experimental data obtained recently at various installations. Additional experimental and analytical work is required to determine the exact value of the local steam void in the TCR-TE core and the local boiling pressure drop.

4.3.5 Stability

Extensive tests were conducted by WAPD-Bettis (Reference 5) to determine if any differences existed between natural circulation and forced circulation fluid mechanics, heat transfer and DNB. The single channel flow results of these tests are presented in Figure 13. The rising parts of the curves are the stable regions. For the 0.210 in. wide channel, flow is stable until approximately 15% exit quality. This corresponds to a flow rate of approximately 5×10^5 lb/hr/ft² and a heat flux of 5.0×10^5 BTU/hr ft², at 1200 psia and an inlet sub-cooling of 109°F.

The corresponding conditions for the TCR-TE are a 0.250 in. wide channel, an inlet sub-cooling of 62°F and an average flux of 0.87×10^6 BTU/hr ft². On the curve shown the TCR-TE conditions are at the very beginning of the rising part of the curve. The peak flux of 3.0×10^5 BTU/hr ft² is still on the rising part of the curve. While the TCR-TE sub-cooling pressure and channel width are slightly different from the parameters of the channel tested, the TCR-TE is still considered to be stable over the entire range of operation since a decrease in sub-cooling decreases stability and an increase in channel width in the range considered increases stability.

There is no danger of damage to the core due to inadequate flow for any power level at which the core may be operating. This is clearly illustrated by Figure 14, which presents coolant flow as a function of power output. During plant start-up and decay heat removal, a very low level of power production in the reactor core results in a relatively high coolant flow. Half of full load coolant flow is achieved at only 15% power and 25% coolant flow is obtained at approximately 4% power.

FLOW STABILITY VS CHANNEL SPACING

FIGURE 13

REACTOR POWER VS COOLANT FLOW

FIGURE 14

4.3.6 Departure from Nucleate Boiling - (DNB)

The ratio of the DNB heat flux to the maximum steady state heat flux is termed the DNB ratio. The TCR-TE DNB ratio is high; thus the TCR-TE is not DNB limited. The DNB correlation used in the design is the Bettis correlation found in WAPD-R-(TH)-583 (Reference 6). This correlation expresses the DNB heat flux as a function of the channel length, pressure, and the enthalpy at the point of the minimum DNB ratio.

4.3.7 Comparison of Forced and Natural Convection Systems

As a result of extensive experimental work on natural-circulation systems (Reference 5) with water at 800 to 2000 psia under non-boiling, local boiling and bulk boiling conditions, the following conclusion was reached: Pressure drop, burnout heat flux and riser density measured under natural-circulation conditions are no different from those measured with forced circulation at the same fluid conditions provided that no large flow fluctuations are present.

5. PRIMARY SYSTEM PRESSURE VESSEL AND RELATED EQUIPMENT - CASE I

5.1 General

In the Case I plant arrangement the entire primary system is contained within one pressure vessel. The reactor vessel, thermoelectric heat exchanger, and the pressurizer vessel are each a sub-assembly which, when connected together, comprise the primary vessel. This vessel arrangement is shown on Figure 15. The lower portion of the primary vessel comprises the reactor vessel and contains the nuclear core. The heat exchanger portion contains the thermoelectric tubes and forms the middle portion of the primary vessel. This sub-assembly is attached to the reactor vessel by means of a bolted-flanged connection. The pressurizer vessel, which facilitates pressurization of the primary system during normal operation and accommodates coolant volume changes resulting from load transients, provides the top closure for the primary vessel. It is attached to the thermoelectric heat exchanger by means of a bolted-flanged connection. The entire primary vessel assembly is contained within the shield water tank.

With the exception of the top of the pressurizer, the primary vessel is filled during normal operation with primary coolant water. This coolant absorbs energy in the form of heat during its passage through the nuclear core. Subsequently, by thermal syphoning action, the hot coolant flows up inside the reactor vessel internals, through the chimney riser in the thermoelectric heat exchanger, and to the top of the heat exchanger where it flows radially outward through ports in the chimney riser. The hot coolant then flows down through the annular portion of the heat exchanger which houses the thermoelectric tubes. In its passage through the TE tube bundle the primary coolant gives up the heat energy absorbed during its flow through the nuclear core. Upon leaving the tube bundle the cold primary coolant flows down through the annular section of the heat exchanger, past the supports for the reactor vessel internals, past the thermal shield, to the bottom of the reactor vessel, and to the core inlet. The primary coolant water then repeats the cycle. The heat given up by the primary coolant in passage through the thermoelectric tube bundle is dissipated from the plant by means of the cooling water which is circulated through the inside of the TE tubes.

In order to provide the necessary thermal driving head, to promote the required primary coolant flow, the center of the thermoelectric tube bundle is located approximately 10-1/2 ft. above the center of the nuclear core.

PRIMARY SYSTEM PRESSURE VESSEL AND RELATED EQUIPMENT TCR-TE CASE 1

FIGURE 15

All pressure containing parts of the primary vessel which experience primary coolant conditions are designed to withstand a pressure of 1500 psia at a temperature of 600°F. In order to achieve lightness in weight, all pressure containing members are sized in accordance with the requirements of the "Tentative Structural Design Basis for Reactor Pressure Vessels and Directly Associated Components" (Reference 7). In a further effort to reduce weight, it is proposed that most of the ferritic pressure carrying members be fabricated of United States Steel Company's HY-80 material. This material has an allowable membrane design stress at 600°F of 35,000 psi as compared to 27,000 and 18,000 psi for ASME-A-302 and ASME-A-212 Grade B, the more common pressure vessel materials. In addition to affording reduction in weight the HY-80 material possesses excellent low temperature impact properties.

5.2 Reactor Vessel

The reactor vessel subassembly is a right circular pressure vessel with a flanged closure at the top and a hemispherical head at the bottom. The TE heat exchanger provides the upper closure for the reactor vessel and is attached by means of a bolted and gasketed flange joint. The reactor vessel has an internal diameter of 39 inches, and its overall length from the bottom of the hemispherical head to the top of the closure flange is approximately 9 ft. 11 in.

The upper portion of the reactor vessel is of forged construction and may be HY-80, A-302 or A-212 material. The choice may be deferred until some later date as it has little effect on weight considerations. The forging is clad with approximately 0.100 inch thick Type 304 stainless steel over those surfaces in contact with the primary coolant. The lower cylindrical section of the reactor vessel and the bottom closure head are fabricated of solid Type 316 stainless steel. The cylindrical section is 1-7/8 in. thick and the bottom closure head is 15/16 in. thick. An austenitic material was chosen for these items because of their proximity to the nuclear core. The austenitic stainless steels do not undergo pronounced radiation damage effects as do the ferritic steels. The combination of ferritic and austenitic materials in the reactor vessel requires that a bi-metallic transition weld be employed in the vessel shell. The location of this transition weld is chosen so that it is not in the high neutron flux area. There has been a considerable amount of experience with the use of bi-metallic welds in the nuclear industry, and no insurmountable problems are anticipated. Special engineering effort is required, however, in the selection of the welding procedure and materials and extra care must be exercised during the fabrication of the weld.

The closure joint between the reactor vessel and the heat exchanger employs 40 two-inch diameter studs. Two gaskets, with a leak-off annulus between them, are furnished to provide the pressure seal. Should any leakage occur past the inner gasket, it would be contained by the outer gasket and piped away through the leak-off piping to the waste disposal system. Through the utilization of radiation shielding, access to the flange is permitted shortly after reactor shutdown and it is proposed that impact wrenches be employed when making and breaking the flange joint. All closure operations may be performed by maintenance personnel standing on the shielded deck of the primary tank.

In order to reduce the heat generation within the reactor vessel wall, a thermal shield is provided which surrounds the core radially. This thermal shield is segmented to facilitate installation, and is positioned and supported within the vessel by means of brackets attached to the lower end of the reactor vessel's cylindrical section. These brackets are fabricated of solid stainless steel and are attached to the vessel by welding.

The reactor vessel is supported in the shield water tank by means of a cylindrical skirt. This skirt is attached to the vessel's closure flange by welding and is bolted, at the bottom, to the deck of the shield water tank. The support skirt is fabricated of carbon steel material.

Although the reactor vessel is surrounded by shield water during plant operation, the construction of the lower portion of the shield water tank is such that the thermal insulation on the reactor vessel will not become wet. Therefore, a standard, high quality, high temperature, insulation is employed. The insulation about the outside of the support skirt does come in contact with shield water, and it is made water-tight by "canning" with stainless steel lagging. With the exception of the closure flange area the reactor vessel is completely insulated prior to shipment.

The auxiliary system connections to the reactor vessel are located as high as possible on the vessel. Pipes leading from these connections are gathered together in an orderly manner and are taken to a convenient location where they are connected by flanges to the piping from the auxiliary systems.

In addition to the nuclear core, the reactor vessel contains the following internals: lower and upper core support grid plates, core baffle, and thermal shield. The lower core support grid plate, as the name implies, supports and positions the core fuel elements. It is bolted to the core baffle which, in turn, is bolted to a support barrel. The core baffle is an irregular shaped sleeve of plate

construction which surrounds the core. Its function is to prevent coolant from by-passing the core and to separate the cold coolant returning to the core from the hot coolant flowing up through the core. The upper core support grid plate is positioned by means of a support barrel and its function is to guide the upper end of the fuel elements and to support the control rod stops. The hot primary coolant as it leaves the core is contained and directed up toward the heat exchanger section through the core support barrels. All of the reactor vessel internals are supported from brackets attached to the I.D. of the reactor vessel near the closure flange. All internals are fabricated from Type 304 stainless steel.

Since the reactor vessel shell weighs approximately 13,000 lbs, and the lower portion of the shield water tank about 15,000 lbs, it is possible to ship these items assembled as a single package. No separate shipping skid is believed to be required as the shield water tank assembly possesses sufficient structural rigidity.

5.3 Pressurizer

The integral pressurizer section is a cylindrical pressure vessel with a hemispherical head at the top and a bolted-flanged connection at the bottom. It has an inside diameter of 48 inches and measures approximately 6 ft in height. The vessel has an effective internal volume of 37 cubic feet and, during normal operation, the upper portion of the pressurizer contains a 28 cu. ft. steam bubble. The entire pressurizer shell is fabricated from HY-80 material and is clad with approximately 0.100 inch of Type 304 stainless steel. In order to reduce the overall height of the primary vessel, the control rod drive mechanisms are "canned" and are located inside the pressurizer vessel (See Section 5.4).

Electric resistance heaters are employed in the pressurizer vessel for initial heating of the contained water and to make up for subsequent insulation heat losses. Approximately 46 KW of heater capacity are supplied in a single row of 40 heaters spaced equally around the vessel periphery. The heaters are of the bayonet type with an outside diameter of 0.553 inch. They are rated at 55 watts/sq. in., with the installed capacity being sufficient to heat the pressurizer water volume (9 cubic feet) at a rate of about 150°F/hour. The heaters are located below the low water level and are installed in the pressurizer by means of heater wells. These wells are attached to the vessel by welding, with the heaters being connected to the wells through the use of a mechanical pressure type fitting. A leak-tight pressure connection is also furnished between the heater wires and the heater sheath. This arrangement employing wells facilitates the replacement of heaters without draining the pressurizer vessel, as well as affording additional protection against leakage in the event of heater sheath failure. Both the heaters and the wells are designed to withstand collapsing pressure and are fabricated of Type 304 stainless steel.

The closure joint between the pressurizer vessel and the heat exchanger portion employs 20 two-inch diameter studs. Two gaskets are employed with a leak-off annulus between them to provide the pressure seal. Should leakage occur past the inner gasket, it would be contained by the outer gasket and subsequently piped away to the waste disposal system.

Nozzles are provided on the vessel shell for the connection of safety valves, a surge line, the spray line and instrumentation. Section 10 includes a line diagram of the associated pressurizer piping systems.

A thermal baffle plate is provided in the bottom of the pressurizer vessel to prevent the interchange of the saturated water in the pressurizer with the subcooled water in the TE heat exchanger. To facilitate later experiments with a saturated reactor coolant cycle, the baffle plate arrangement is designed so that it is removable.

The total weight of the pressurizer vessel assembly, including mechanisms and heaters, is approximately 6,900 pounds.

5.4 Control Rod Drive Mechanisms

The control rod drive mechanisms are of the latch-type magnetic jack design, which is described in greater detail in YAE-155 (Reference 8). The mechanisms are capable of raising and lowering the control rod - fuel follower assemblies at an average speed of four inches per minute. The standard mechanism design has been modified as shown in Figure 16. The pressurizer encloses the mechanisms in a way such that no height penalty results from adding the pressurizer to the primary vessel closure. Each modified mechanism consists of an outside and an inside pressure shell (A & B) with an annular space (C) between shells. The two shells are joined together at their lower extremity, and the annulus is open to ambient conditions, allowing torus-shaped magnet coils (D, E, & F) to be fitted into the space. A steam bubble is maintained above the free surface of water in the pressurizer volume which surrounds the mechanism outer shells. Electrical heaters (G) supply heat to the pressurizer, and a thermal barrier (H) maintains a small amount of sub-cooling in the reactor portion of the vessel. Electrical coils on the mechanism are made with ceramic insulation to obviate the need for cooling; these coils will then operate at slightly above the saturation temperature for the operating pressure selected.

The following advantages are obtained with the proposed control rod mechanism design:

- 15 -

TCR-TE CONTROL ROD DRIVE MECHANISM

FIGURE 16

1. The pressurizer can be incorporated into the primary vessel closure without increasing the overall height of the reactor.
2. Present latch-type magnetic jack mechanism designs can be adapted to the integral pressurizer concept.
3. Individual mechanisms can be removed and replaced by breaking a single seal weld at (J).
4. Electrical coils can be replaced without opening the primary system.
5. The reactor core and the mechanism thimbles are directly communicative so that no differential pressures can exist across the control rod system. This precludes the possibility of a rod ejection accident caused by pressure transients.
6. Reactor head removal can be accomplished without removing individual mechanisms, since the drive shaft assemblies are completely free from the mechanism after every scram.

5.5 Thermoelectric Heat Exchanger Assembly

The thermoelectric heat exchanger assembly is a vertical, right circular pressure vessel with a bolted-flanged connection at the top and the bottom. It is approximately 9 ft. 7 in. long, flange face to flange face. The shell is divided internally into two sections by the cylindrical chimney riser; i.e. a circular inner section and a surrounding annular section. The inner section houses the control rod drive shafts and furnishes the flow path for the hot coolant rising from the core, while the outer annular section contains the TE tube bundle. United States Steel Company's HY-80 material is specified for this application since it possesses high strength properties which permit weight reductions, as well as very good low temperature impact properties.

The TE tube bundle contains approximately 640 U-shaped tubes which penetrate the upper portion of the heat exchanger shell. The tubes are positioned in circular rows which are 0.975 inch apart, with the tube spacing on the rows also being 0.975 inch. Because of an unequal number of tubes in adjacent rows, the reference design tube layout pattern results in a situation where the size of the flow areas between the tubes is irregular and the fabrication of the tube bundle into the vessel is somewhat unwieldy. Consequently, an engineering program to establish an orderly and more practical tube layout pattern would be undertaken prior to fabrication.

The U-shaped TE tubes are installed into the heat exchanger through holes drilled in the upper portion of the pressure shell. For installation into the shell, the tubes are made up into radial row assemblies and held together by braces. These row assemblies are then individually positioned inside the pressure shell and inserted through the tube holes. In order to provide ultimate reliability against leakage the outer sheath of the tubes is welded to the clad outer surface of the pressure shell. This attachment of the tubes to the shell presents another area in which an engineering program is required. Currently available tube welding procedures must be investigated by the equipment vendor to determine whether or not one can be qualified for this application or if a new welding procedure will have to be developed.

The straight portion of the U-tubes contains the thermoelectric material and has an average length of approximately nine ft. The bent portion of the tubes contains the electrical conductor which electrically ties the TE sections together. The conductor also facilitates connection of the individual tubes into electrical circuits external to the vessel. Outside the heat exchanger, the TE tubes are connected into electrical circuits by means of copper straps. These straps are slipped over the exposed electrical conductors at the edge of the tubes after welding the tubes to the vessel shell (See Fig.5 Sect.3.2). Additional engineering effort will be required at a later date to establish the most desirable method of attaching these straps to the tube conductors.

In connecting the TE tubes to the raw cooling water headers, flexible jumper tubes are employed. Attachment of the jumper tubes to the individual TE tubes is accomplished through the use of commercial type mechanical connectors. Since the cooling water system operates at low temperature and low pressure, there is no concern over the adequacy of the mechanical connectors. This method of connecting the cooling water system to the heat exchanger offers a number of advantages, including reliability. Through the use of jumper tubes the electrical connectors, which join the TE tubes, are located in a normally dry area and the electrical insulation requirements for the copper straps are, therefore, relatively simple. Another advantage of this arrangement is that, in the event of leakage in the tube joint area, access for repair is possible after disconnecting the jumper tubes. Should leakage occur as the result of tube weld failure, repair welding can also be accomplished. In the event of leakage through the tube wall the failed tube may be isolated by blanking-off the tube end.

Baffles are provided at the top of the tube bundle to distribute the coolant as it flows outward from the chimney riser. A baffle is also employed in the circular lane formed by the bend in the TE U-tubes. This baffle is segmented and is inserted through the tube lane as the tube bundle is fabricated.

The chimney riser assembly consists of a hollow cylinder 19 inches in outside diameter, five control rod drive shaft guide tubes, and the necessary members for supporting the guide tubes in the chimney. Should it be found necessary at a later date to reduce the heat transferred across the chimney wall, double walled construction could be employed.

The cooling water system external to the heat exchanger employs two ring headers. Both the inlet and the outlet water headers are divided into five sections. Stop valves may be installed in the piping supplying these headers to permit isolation of any corresponding section of the TE tube bundle. These headers are fabricated of four-inch nominal O.D. carbon steel pipe and are supported off the heat exchanger shell. The jumper tubes are attached to the headers by means of threaded connections.

Thermal insulation is provided on the heat exchanger assembly to reduce the heat losses. Because the bottom of the heat exchanger section is submerged in shield water during normal operation, the insulation on the lower portion of the shell is made water-proof by "canning". The insulation at the top of the vessel is a standard, high quality, commercial material. In the closure areas the insulation is fabricated into sections to permit removal for closure area access.

Because of weight considerations, it is not proposed to ship the chimney riser assembly integral with the heat exchanger assembly. Other items requiring separate shipment are the cooling water headers and the jumper tubes. These items must be assembled to the heat exchanger during field erection. The weight of the heat exchanger assembly, i.e. pressure shell and TE tube bundle, is 25,900 lbs.

5.6 Plant Containers

The containers for the TCR-TE primary plant consist of an arrangement of two tanks; a shield water tank and a refueling tank. These tanks are designed to allow separate shipment while facilitating their attachment in the field to form a single structure.

The shield water tank is divided into two sections. The lower section of the tank houses the reactor vessel, and supports the entire primary vessel. It is permanently flooded with water to provide radiation shielding. This lower portion of the shield water tank is made up of two concentric cylindrical shells connected together at the top in a box flange construction and, at the bottom, through a common base. The reactor vessel is located inside the inner shell, with the shield water being contained in the area between the inner and outer shells. The shells are of rib and column construction and

are covered with a thin skin. The box flange is of plate construction, with a rather heavy plate being employed to provide a substantial deck on its upper surface. Both the reactor vessel and the upper portion of the shield tank are attached to this deck. Lead shielding bricks are also positioned and supported from this deck.

Seven water tight thimbles are provided in the shield water tank to facilitate positioning of nuclear instrumentation in a dry atmosphere about the reactor vessel. These thimbles are equally spaced around the reactor vessel, extend into the shield water, and are supported off the deck plate. The thimbles are sealed by plugs set into the deck after installation of the nuclear instrumentation.

The upper portion of the shield water tank is attached to the lower portion in the field by bolting. It is a single wall tank and is of identical construction as the bottom portion; i.e., ribs, columns and skin. However, this portion of the tank is not, in cross section, a closed cylinder since approximately 80° of arc (adjacent to the refueling tank) are cut away. Since the upper portion of the refueling tank has a similar configuration, these cut out portions of the shells permit the transfer of fuel elements from one tank to the other during refueling operations. The upper section of the shield water tank houses the TE heat exchanger and the pressurizer vessel. During normal operation the shield water tank is partially flooded, while during the refueling operations both the shield water tank and the refueling tank are completely flooded. To control radiation streaming through the tops of the tanks during plant operation, both of the containment tanks are furnished with covers which may be flooded with shield water.

Both portions of the shield water tank are furnished with two longitudinal stiffening beams which are located at the two corners adjacent to the refueling tank. These beams facilitate attachment of the refueling tank to the shield tank and should also accomplish the requirements of a shipping skid in meeting aircraft shipping limitations.

The refueling tank is also a single walled, water tight circular tank of rib, column and skin construction. The bottom portion is a closed cylinder in cross section, while in the upper portion approximately 80° of arc are cut away, as described previously. New and spent fuel elements are stored in racks in the bottom portion of the tank. Fuel assemblies are transferred to and from the shield water tank through the cut away section during refueling operations. Normally the refueling tank is partially flooded to permit the storage of spent fuel elements.

The design considerations for these tanks include the collapse pressure of the surrounding external back fill material, the weight and bursting pressure of the contained water, and the weight of the supported equipment. With the exception of the stiffening beams, which may be carbon steel, the tanks are fabricated entirely of stainless steel material. The outside diameter of the tanks is approximately 102 in., with the overall length of each tank being 28-1/2 ft. The lower portion of the shield tank weighs approximately 15,700 lbs., the upper portion 14,000 lbs., and the refueling tank 15,000 lbs.

6. PLANT THERMAL AND HYDRAULIC PERFORMANCE - CASE I

6.1 General

The results of thermal and hydraulic investigations on the plant primary and secondary coolant systems are presented in the Summary of TCR-TE Plant Data, Table 2, in Section 2. The equations and sample calculations are given in Appendix E. Figure 17 presents the TCR-TE Case I coolant thermal performance. The TE tube thermal characteristics are discussed in Section 7.

6.2 Primary System Thermal and Hydraulic Performance

Certain ground rules (as elaborated in Section 1) were assumed as the basis for the TCR-TE Case I thermal and hydraulic performance calculations. First, a TCR-type core (Reference 3) was utilized, with a 10 MW(th) rating. The TCR has a thermal (natural) circulation primary coolant system of the pressurized water type. To this TCR core, a thermoelectric heat exchanger was added integrally within the reactor vessel and located a required distance above the core to obtain the thermal driving force necessary for the desired primary coolant circulation rate. This system is shown in Figure 3. The coolant removes the heat from the core, transports it to the TE heat exchanger tubes where the heat is removed, and then returns to the core to complete its cycle by thermal circulation. The core inlet temperature is 498°F, the exit temperature is 552°F (10° sub-cooled), and the core average temperature is 526°F. As in the case of the TCR Study, a primary system pressure of 1150 psia was assumed for the TCR-TE reference design. Section 4.3 and Reference 3 give a detailed description and performance data on the thermal and hydraulic aspects of the TCR-TE core.

In a thermal (natural) circulation flow system, the flow rate is determined by balancing the sum of all the unrecoverable pressure drops in the system against the available thermal driving head. This driving head is equal to the integrated density and height difference of the coolant around its closed loop. Appendix E proceeds through this analysis. A summary of the results of this calculation for the TCR-TE Case I reference design is:

Total primary system unrecoverable pressure drop	35.3 psf
Thermal driving head (center line of core to center line of heat exchanger)	10.5 ft
Primary flow rate	515,000 lb/hr
Heat exchanger tube primary side average film coefficient	770 BTU/hr-ft ² -°F

TCR-TE THERMAL PERFORMANCE
(CASE I)

FIGURE 17

E. D. SK. 280385 B

The friction factor, loss coefficient and pressure drop relationships from WAPD-217 (Reference 9) provided the basis for the pressure drop calculations. A local boiling friction factor multiplier has been utilized where local boiling occurs in the reactor core.

The thermal and hydraulic calculations in the heat exchanger are based on the "average tube condition" concept. These calculations did not consider the effects of variations in tube lengths from one heat exchanger tube to another, and of changes in flow and power distribution throughout the tube bundle. These variations are not considered to have a significant effect on overall pressure drop, heat transfer or thermal driving force. Average flow velocities are used to define the flow resistance and thermal characteristics. A heat transfer fouling factor of $.0002 \text{ hr-ft}^2\text{-}^\circ\text{F/BTU}$ was assumed on the TE tube primary side.

With the integral type of heat exchanger arrangement used in the reference design the hot reactor primary coolant flows on the outside of the heat exchanger tubes and the lake water secondary coolant flows on the inside of the thermoelectric tubes. It is of interest to note that for thick-walled tubes such as those utilized in the TCR-TE application, the optimum thermal arrangement is to have the better heat transfer medium on the inside of the tubes where the much greater heat flux is present. This is not true in the Case I reference design, since cold lake water has a higher fouling factor than the clean closed-loop primary coolant (.0007 vs. .0002). Increases in the secondary flow rate will not compensate for the adverse difference in fouling factors.

The heat exchanger tubes are 0.850" O.D. and are spaced in an irregular pitch of 0.975 inches. A total of 640 U-tubes containing an average length of 9 feet of TE material are required.

6.3 Secondary System Thermal and Hydraulic Performance

The ground rules for the design of the TCR-TE Case I secondary cooling system are:

1. Direct lake water cooling is utilized.
2. The lake water inlet temperature is 80°F.

The secondary coolant water is pumped directly from a lake into a header arrangement adjacent to the reactor vessel, through the 640 U-shaped thermoelectric heat exchanger tubes, and back to the lake.

Figure 18 shows the effect of secondary flow rates on the plant overall net efficiency. Figure 19 shows the combined effect of secondary flow rate and TE material thickness on plant overall net efficiency. Based on these results, a flow rate of 500,000 lb/hr was selected for the Case I reference design. At this flow rate, the average secondary coolant temperature is 112°F, and the exit temperature is 144°F as shown in Figure 20. These temperatures were obtained by performing a heat balance on the heat exchanger. It can be readily seen that the heat rejection capacity must be the difference between the core thermal output (neglecting thermal losses) and the amount of electrical power generated. The pumping power required for the design flow rate through the Case I secondary system is estimated to be 25 KW.

The secondary fouling factors were varied between zero (clean) and .0011 hr-ft²-°F/BTU in order to show their great effect on performance. Also, since no exact site location can presently be prescribed, this factor must remain a variable. Fouling factors of the indicated low magnitudes require either high grade secondary coolant water or frequent cleaning of the tubes.

Various possible means of improving the Case I performance are discussed in Appendix G. Two of these of major significance are internal finning of the heat exchanger tubes and the use of secondary inlet temperatures lower than the 80°F specified in the reference design.

TCR - TE PERFORMANCE
 EFFICIENCY VS SECONDARY FLOW RATE
 CASE I DESIGN

FIGURE 18

E. D. Sk. 280379B

TCR - TE PERFORMANCE
 EFFICIENCY VS TE THICKNESS
 CASE I DESIGN

FIGURE 19

E. D. Sk. 280383 B

TE-TCR PERFORMANCE - CASE I
SECONDARY COOLANT TEMPERATURES

FIGURE 20

E. D. SK. 280438 B

7. THERMOELECTRIC TUBES - CASE I

7.1 General

The general arrangement of the thermoelectric heat exchanger is shown in Figures 3 and 15. Its mechanical construction and overall performance are described in detail in Sections 5.5 and 8, respectively. This assembly consists of 640 U-tubes, each of 9 ft. effective thermoelectric length (i.e., the straight portion of each tube). The tubes have an external diameter of 0.850 in. and a 0.272 in. I.D. The hot, high-pressure, reactor water circulates on the outside or shell side of the tubes and the cold, low-pressure, secondary water circulates through the U-tubes. In this manner, the reactor core heat is transferred from the primary to the secondary coolant and eliminated from the system. In turn, a high thermal gradient is produced across the tubes which contain a composite thickness of thermoelectric material, thus generating electricity.

For analytical purposes, a thermoelectric heat exchanger tube can be considered as consisting of a large number of "typical" TE couples, with each "typical" couple undergoing average conditions and performing identically. Thus, the performance of a "typical" or average couple is evaluated and accumulated in order to obtain the overall tube performance. The couple's performance is accumulated in series electrically, and in parallel from a heat transfer standpoint. This technique greatly simplifies the effort involved; and, the error arising due to this approach is less than that of most of the heat transfer, hydraulics and TE correlations utilized.

7.2 Mechanical Construction of Thermoelectric Tubes

7.2.1 Description

Thermoelectric heat exchanger tubes constructed in the swaged series-tubular arrangement, as shown in Figures 5 and 21, have been chosen for this design study. (Appendix J contains a discussion of the relative merits of various thermoelectric element arrangements.) The assembly contains the thermoelectric material, insulation and electrical conductors stacked in a series of hollow discs. This assembly is sheathed by insulation and restraining tubes. The electrical current flow path (shown in Figure 5) is best described as an "axial-radial stepped" path which alternately flows radially through the TE material (reverses direction in the n and p legs) and axially through the inner and outer conductor rings, for the complete length of the TE material in a heat exchanger tube. These tubes are then connected by end straps to form the generator electrical network.

FIGURE 21

In detail, the thermoelectric tube assembly, as shown in Figures 5 and 21, consists of the following eight basic components:

1. An inside stainless steel tube having a 0.049 in. wall thickness. This component extends continuously for the full length of the tube and functions as a protective and pressure-containing member.
2. An inside cold insulation (Al_2O_3) having a 0.005 inch wall thickness. This component extends continuously for the full length of the tube and insulates the electrical circuit from the inside tube.
3. The inside or cold conductor (iron-coated copper), which has a 0.0475 in. wall thickness. This component is interrupted at each couple length and carries the electrical current from TE element to adjacent TE element in the tube axial direction. The iron coating is used because of the excellent compatibility with lead telluride and consists of a 0.005 in. thickness between the TE material and the copper.
4. Thermoelectric material rings or elements of 0.120 in. radial thickness with p and n-types stacked alternately. Each type of TE material measures approximately half the couple length. There is one p-type and one n-type element per couple. These components generate electricity when subjected to a temperature gradient.
5. Insulation washers (Mica), having a 0.005 in. thickness. These are located between the TE material elements and also interrupt the conductor rings in order to establish the electrical current flow path.
6. The outside or hot conductor (iron-coated copper), which has a 0.045 in. wall thickness. This component is interrupted at each couple and carries the electrical current from TE element to TE element in the tube axial direction. Again, the 0.005 in. thick iron coating is placed between the copper and the TE material for compatibility purposes.
7. The outside insulation (Al_2O_3) having a 0.0075 in. wall thickness. This component extends continuously for the full length of the tube and insulates the tube internal electrical circuit.
8. An outer stainless steel sheath with a 0.015 in. wall thickness. This component extends continuously for the full length of the tube and serves as a protective coating and pressure containing member.

The basic components noted above are assembled in a free stack (of close tolerances) and fabricated into a final tight rigid thermoelectric tube assembly by swaging. The assembly is then sintered and annealed.

It is anticipated that, with proper material selection, the hot external water and pressure will serve to tighten up the tube assembly. Due to the considerable pre-stressing from swaging, the thermoelectric material bears strongly against the hot and cold conductor sleeves. This serves to preserve the metallurgical bonds obtained during sintering, thus providing negligible interface resistances to electrical and thermal flow. This is one of the inherent advantages of the series-tubular geometry, in contrast to the flat plate type of thermoelectric elements where the contact or interface resistances between the thermoelements and the conductors are considerably greater, and undesirable mechanical means (springs, clamps, etc.) of improving contact are required.

In accordance with the study contract requirements, p and n doped lead telluride TE material was adopted for the TCR-TE Case I reference design. The thermoelectric material wall thickness of 0.120 inch was selected as a reasonable compromise between maximum efficiency and minimum TE material utilization (See Figure 19).

For a TE couple axial length of 0.82 in. and a thickness of 0.120 in. (values selected for the reference design), 83,300 couples are required to produce the Case I power. For the TE material properties used, the axial length of the average p-leg is 0.483 in., and the average n-leg is 0.327 in. long.

The thermoelectric material is contained only in the straight portions of the heat exchanger tubes. Annular copper tubes of approximately 0.080 in. wall thickness conduct the current around the curved U-bend and through the curved top portions of the tubes, serving to complete the generator circuitry. Thick thermal and electrical insulation is also located in these areas, to minimize electrical losses and heat losses from the primary to the secondary coolant. Thus, a greater heat flux can be obtained in the uninsulated (i.e., thermoelectric material bearing) portions of the heat exchanger tubes; this produces the desired greater thermal gradient across a given thickness of thermoelectric material.

7.2.2 Fabrication

The thermoelectric tubes will be fabricated by a technique known as rotary swaging. This technique has been extensively investigated (Reference 10) recently by the Westinghouse Atomic Power

Department under AEC Contract AT-(30-3)-500, and appears to offer significant potential for the fabrication of thermoelectric generator components of the type being considered in the TCR-TE design study. In this operation, hollow cylinders of thermoelectric material (pre-stressed rings of p and n-type) are initially stacked with the appropriate insulators and electrical conductors onto a rod or tube with mandrel, in the sequence shown in Figure 5. This assembly is then sheathed in a suitable protective material and insulation. The unit is sealed by welding end closures on the inside and outside tubes. If a rod were utilized (rather than a tube with mandrel), boring to the required I.D. would be necessary after swaging.

After the thermoelectric tube assembly has been sealed it must be reduced to provide a tight compact assembly, and to further compress the TE material for efficient thermal and electrical characteristics. This is accomplished by swaging. The amount of reduction is calculated to a value which will bring the TE material to essentially 100% theoretical density. The swaging operation can be performed at room temperature or at some elevated temperature. Multi-couple thermoelectric elements have been swaged at temperatures as high as 750°C. When cold swaging is employed, a subsequent sintering treatment must be performed. Present sintering procedures are conducted in the temperature range of 700° - 800°C. This sintering operation forms a metallurgical bond between the conductors and the TE elements, thus minimizing undesirable electrical and thermal resistances at the interfaces.

Hot swaging has been investigated recently and shows promise as a possible alternate method to cold swaging and sintering. The justification for hot swaging is based on the idea that the simultaneous action of pressure and temperature will favor more complete densification of the thermoelectric material at a given reduction while still providing small interface resistances. The initial results of hot swaging have been quite encouraging (Reference 11).

Another promising technique which is presently under investigation to improve the density of the TE material is pressure sintering. By this method, the swaged thermoelectric assembly would be placed in a high temperature autoclave and sintered under pressure. The simultaneous application of temperature and pressure forces the clad tightly against the TE material and minimizes any tendency toward gap formation, thus reducing interface thermal drops and electrical resistances.

Since the TE materials are so completely encapsulated, any volatilization of the TE materials is virtually eliminated by using the swaged series-tubular configurations. Thus, longer life with less degradation in thermoelectric performance is possible.

The rotary swaging technique combined with the series tubular concept is also ideal for mass production fabrication of full length thermoelectric tube assemblies having multiple couple arrangements.

7.3 Thermal Characteristics of Thermoelectric Tubes

Appendix E outlines in detail the thermal characteristics analyses performed in this study. Figure 22 summarizes these calculations. It describes (for the TE tube assembly shown in Figures 5 and 21) the attainable temperature gradient across the TE material for any thermoelectric material thickness, secondary fouling factor and overall primary to secondary bulk coolant temperature differences. In these calculations the internal diameter of the tube varied as the TE material thickness was changed. The tube O.D. (0.850 in.), and the thicknesses of conductors, insulations and inside and outside tube walls were held constant.

The results of this analysis are presented in Figures 18, 19, and 23, for the TCR-TE Case I design. Figures 19 and 23 illustrate the effect of TE material thickness on overall plant net efficiency and length of TE tubing. Based on these results, a thermoelectric material thickness of 0.120 in. was selected for the reference design. Figure 18 gives the effect of secondary flow rate on the overall plant net efficiency. A flow rate of 500,000 lb/hr was selected as being approximately optimum. These results are based on a secondary coolant inlet temperature of 80°F and a TE material conversion factor, $\eta_{p.c.}$, of 0.161. The tube secondary-side fouling factors were varied between zero and 0.0011 hr-ft²-°F/BTU. Where PbTe thermoelectric material with the properties described in Appendix I is utilized, $\eta_{p.c.} = 0.161$ corresponds to a TE material thickness of 0.120 in. and a TE couple length of 0.82 in.

Figure 21 presents the average temperature profile across the Case I TE tube reference design cross section, for an average secondary-side fouling factor of 0.0007. The primary coolant average bulk temperature is 526°F, the secondary coolant average bulk temperature for a flow rate of 500,000 lb/hr is 112°F. The heat flux, based on the tube outside diameter, is 24,200 BTU/hr-ft²-°F. (This assumes a 10% heat loss through the tubes for those sections which do not contain thermoelectric material.) The heat transfer coefficient through the composite tube for a thermoelectric material thickness of 0.120 in. was 58.4 BTU/hr-ft²-°F. Tables 8a & 8b summarize the thermal characteristics for the TE tube design.

For the 0.0007 fouling factor chosen for the reference design, the total heat exchanger effective thermoelectric length, $\bar{L}$, required to produce the necessary electrical power is 5525 ft. This assumes 100% heat exchanger effectiveness. A 4% factor is added to this figure to compensate for some heat exchanger ineffectiveness. Thus 5750 ft. of tubing would be required; in the reference design this total consists of 640

E. D. SK 288274C

TCR-TE PERFORMANCE
TE TUBE THERMAL CHARACTERISTICS

CASE I
Figure 22

TCR - TE PERFORMANCE
 TE MATERIAL THICKNESS VS TOTAL LENGTH
 CASE I DESIGN

FIGURE 23

E. D. Sk. 280378 B

TABLE 8(a)

TCR-TE CASE I DESIGN THERMAL CHARACTERISTICS

Primary Coolant Average Bulk Temperature, T_{ave} (515,000 lbs/hr)		526°F	
Secondary Coolant Average Bulk Temperature, T'_{ave} (5000,000 lbs/hr and 80°F T_{in})		112°F	
Overall Average Temperature Difference, T_o		414°F	
Thermoelectric Material Thickness, t_{TE}		0.120 in.	
Secondary Fouling Factor, r_i	0 (clean)	.0007	.0011
Overall TE Tube Heat Transfer Coefficient, U_o (BTU/hr-ft ² -°F)	65.7	58.4	54.5
Total Effective Tube Length, $\bar{L}$ (ft)	4920	5525	5920
Overall Tube Heat Flux $(q/A)_o$ (BTU/hr-ft ²)	27,200	24,200	22,600
TE Material Temperature Gradient, ΔT_{TE} (°F)	262.0	234.1	217.6
TE Hot Side Temperature, T_h (°F)	924	930	935

TABLE 8(b)

Thermal Characteristics at Design Conditions

Temperature Profile for the Case I TCR-TE
Heat Exchanger Tubes; Tube Design per Figure 5

$$r_i = .0007$$

$$t_{TE} = .120''$$

$$O.D. = 0.850''$$

<u>Location</u>	<u>Uncorrected Thermal Resistance</u>	<u>Thermal Resistance Corrected to Tube O.D.</u>	<u>Representative ΔT ($^{\circ}F$)</u>	<u>Actual Temp. ($^{\circ}F$)</u>	<u>% of Total ΔT</u>
			$\left(\frac{q}{A}\right)_o = U_o \Delta T_o = 24,200$		
1) Secondary T'_{ave}	--	--		112	--
2) Secondary film ₁ drop $1/h_i = \frac{1}{3300}$	.000300	.000937	22.7	134.7	5.5
3) Secondary fouling film - r_i	.000700	.002188	52.9	187.6	12.8
4) Inside Tube	.000404	.000980	23.7	211.3	5.7
5) Inside Insulation	.000417	.000945	22.8	234.1	5.5
6) Cold Conductor	.000040	.000079	1.9	236.0	.5
7) TE Material	.006940	.009690	234.1	470.1	56.6
8) Hot Conductor	.000038	.000040	1.0	471.1	.2
9) Hot Insulation	.000625	.000641	15.5	486.6	3.7
10) Outer Tube	.000125	.000130	3.1	489.7	.7
11) Primary Film Drop - $1/h_o$	.001300	.001300	31.5	521.2	7.7
12) Primary Fouling Film - r_o	.000200	.000200	4.8		1.1
13) Primary T_{ave}	--	--	--	526.0	--
Total		--	414.0		100.0%
$1/U_o =$		.017130			
$U_o =$		58.38			

U-tubes, each having 9 ft. of effective thermoelectric length. This length of tubing requires approximately 83,300 thermoelectric couples, each 0.82 in. in length. The 4% factor was believed to be a minimum reasonable allowance needed. Special baffling and mechanical arrangements will have to be incorporated into the heat exchanger design, to assure that this margin is sufficient. This 4% margin is intentionally held to a minimum, in order to reduce thermoelectric tubing costs.

Greater efficiencies could be obtained both by slight variations in TE material thickness along the axial length of the heat exchanger tubes to correspond to the axial temperature distribution, and by an increase (greater than 0.120 in.) in the TE material thickness. However both of these approaches are considered unwise from an economic standpoint.

Since there are heat sources (Joule and cold junction Peltier heating) and heat sinks (hot junction Peltier cooling) in the thermoelectric material, the thermal analysis is not a simple conduction calculation for a concentric tube. In fact, even the magnitudes of the sinks and sources are dependent upon the electric current drawn from the generator. This is because the Peltier effect is proportional to the current flow and the Joule effect is proportional to the square of the current flow. Joule heating of the thermoelectric material is small except for high currents. The Peltier effect causes part of the heat to be absorbed in a sink at the hot junction and a lesser amount to be produced at the cold junction in normal operation of the generator. In Appendix E, a "mean effective thermal conductivity" is derived for the thermoelectric material characteristics, considering both of these effects. The following equation evolved from this derivation:

$$\frac{\bar{k}_{\text{eff}}}{k_{\text{co}}} = 1 + Z_M T_h \left[\frac{1}{1 + M} - \frac{e_{\text{ct}}}{2} \left(\frac{1}{1 + M} \right)^2 \right]$$

The $Z_M T_h \left(\frac{1}{1 + M} \right)$ term is the Peltier effect and the $Z_M T_h \frac{e_{\text{ct}}}{2} \left(\frac{1}{1 + M} \right)^2$ is the Joule heating effect in the thermoelectric material. This "effective thermal conductivity" is the ratio of the heat flux drawn by the generator to that flux which would be drawn in the absence of Peltier and Joule effects, i.e., for the open circuit condition. This expression was the basis for the tube thermoelectric material thermal calculations in this study. It is interesting to note that this ratio of conductivities was 1.386 under full power and optimum load conditions for the Case I design. Thus, the increased thermal conductivity which results from incorporating these effects requires greater thermoelectric material thicknesses.

One problem which requires additional investigations is that of the thermal stresses induced in the operation of a composite tube of the type used in the reference design. It appears that a coordinated experimental and analytical effort will be required in order to definitely answer the significant questions. The following observations on this subject resulted from preliminary studies at the Westinghouse Atomic Power Department:

1. Fabrication techniques should be adopted which will minimize the thermal stress problem. Sintering at 750°C and cooling to room temperature imposes serious burdens on the composite tube assembly. Pressure sintering may help this problem.
2. Experimental data on physical and mechanical properties, especially for the TE materials and copper alloys, are badly needed.
3. Radial mechanical and thermal stresses due to system pressure and temperature gradients do not appear to be a serious problem for the TCR-TE design and conditions. However, careful consideration must be given to the selection of materials with thermal expansions that are compatible with the design and its application. For example, different types of stainless steel with compatible thermal expansion should be considered for outside and inside tubes.
4. Axial thermal stresses appear to be a problem and will require extensive experimental and analytical investigations. Thermal bowing and ratcheting must also be investigated.
5. It appears that the insulation material may crack during the heating up process while sintering. When the tubes are brought back to room temperature, the contained materials will shrink together, but fractures will still be present. However, such cracks or fractures of small width should not degrade performance of the assembly.
6. Preliminary calculations show that the 0.049" wall thickness of the inside tube can be reduced to approximately 0.020". If so, all other component diameters can also be reduced. This will reduce the overall size of the heat exchanger assembly and increase the overall strength of the composite tube assembly.
7. A thorough investigation should be carried out on the thermal cycling effects during a full life of the TCR-TE generator - heat exchanger.
8. Preliminary results indicate that the metallurgically-bonded interfaces between the copper-iron conductors and the thermoelectric material in the reference design will be preserved during normal anticipated operation of the TCR-TE system.

Research and development studies in the above areas are recommended in Section 2.2.8 of Appendix A.

7.4 Thermoelectric Performance Calculations

Thermoelectric performance calculations for the TCR-TE, Case I, design are presented in detail in Appendix F. The results of these calculations are given in the Summary of TCR-TE Plant Data, Table 2, Section 2. Table 4 in Section 3.2 also summarizes the TE performance in somewhat greater detail. The standard thermoelectric relationships, such as those given by Ioffe (Reference 12) were used in the TCR-TE performance analysis.

Figures 24 and 25 summarize the results of the TE couple length optimization studies. Figure 24 presents the net efficiencies and numbers of couples required for various lengths of thermoelectric couples. The dotted line represents the reference design selected. Figure 25 shows various couple characteristics such as current flow, electrical resistance and design Figure of Merit for various lengths of TE couples. Again the dotted line represents the reference design selected. As noted in Figure 24, net plant efficiencies could be improved above 3.15% by decreasing the couple length. However, a rapid increase in the number of couples would then be required, thus increasing fabrication costs. Also, it can be seen in Figure 25 that, as the thermoelectric couple length is decreased the internal resistance increases, the current decreases and the design figure of merit increases.

The reference design as selected resulted in an axial couple length of 0.82 in. This couple length combined with a TE material thickness of 0.120 in., as determined by the tube thermal characteristic calculations, gives a TE material conversion factor of 16.1%. Based on the considerations given in Appendix I, thermoelectric material with an average thermoelectric material Figure of Merit of $1.85 \times 10^{-3} (^{\circ}\text{C})^{-1}$ was assumed in the calculations. The internal electrical resistance of the reference design TE couple is 203×10^{-6} ohms, the current flow is 126 amps, the design figure of merit is $1.75 \times 10^{-3} (^{\circ}\text{C})^{-1}$ and the gross efficiency is 4.07%, assuming a tube secondary side fouling factor of 0.0007 hr-ft²-°F/BTU. A total of 83,300 such couples are required to produce 407 KW of gross electrical power for the Case I TCR-TE plant.

It is evident from the basic equations (Reference 12) that the efficiency of a couple, if the TE material is optimized for cross-section area, is fully determined by: a) the couple hot and cold junction temperatures, b) the load ratio, M , and c) the properties of the couple material and conductor design. Consequently, the hot junction temperature should be as high as possible, and the cold junction temperature as low as possible in order to achieve maximum efficiencies. It is of interest to note that a reduction in temperature at the cold junction results in a greater increase in efficiency than an equivalent increase in temperature on the hot side, for two reasons. First, the properties of the TE materials are significantly better at the low-temperature end than at the hot end. Second, a greater improvement in the Carnot efficiency is gained,

TCR - TE PERFORMANCE
 NUMBER OF COUPLES AND NET EFFICIENCY
 CASE I DESIGN

FIGURE 24

E. D. Sk. 280381B

TCR - TE PERFORMANCE
 TE COUPLE CHARACTERISTICS
 CASE I DESIGN

FIGURE 25

E. D. Sk. 280382B

since an increase in hot side temperature increases the temperature difference but has the adverse effect of increasing the denominator in $e_{TC} = \frac{\Delta T}{T_h}$.

The quantity $\alpha^2 / (K_{CO} \cdot R_{CO})$, called the design figure of merit, Z_D , is the direct design measure of couple thermoelectric efficiency. Thus, just as the material figure of merit gives a measure of the TE material efficiency, the design figure of merit represents the complete couple efficiency for a fixed design which includes thermoelements, conductors and insulation.

The calculated results are based on the assumption of negligible electrical and thermal resistance at the conductor-TE material interface; it is believed that this can be achieved by utilizing the swaging technique for fabrication of series-tubular arrangements. The calculated efficiencies also reflect optimum generator internal to external resistive load ratios.

8. THERMOELECTRIC GENERATOR - CASE I

8.1 General

The general arrangement of the thermoelectric heat exchanger - generator is shown in Figures 3 and 15 . The mechanical construction of this heat exchanger - generator assembly and the related components are described in detail in Section 5.5. This assembly is located integrally within the reactor pressure vessel and consists of 640 U-tubes of 9 ft. average length, containing thermoelectric material in the straight portions of the tubes. Each of these tubes consists of a set of series-arranged TE couples ($9 \text{ ft} \times 12/0.82 = 132 \text{ couples/average tube}$) which generate electricity. These tube assemblies are connected in series and parallel by end straps to form the desired generator internal electrical network

A thermoelectric generator is analogous to many small batteries in a series-parallel arrangement. Each p and n-type thermoelement would represent a battery which generates electricity with the terminals connected in series (voltages additive). Groups of these would then be connected in parallel (current additive) to form the desired generator network.

From the standpoint of obtaining high voltages (to minimize internal I^2R losses), a maximum number of series-connected couples is desirable. However, a maximum number of parallel hookups is also desirable, for reliability. Thus, a compromise between these two features is necessary.

Figure 5 illustrates the arrangement of the thermoelectric couples in a typical tube assembly and shows the resultant current circuit which is induced. This current path through the tubes is best described as an "axial-radial stepped" flow path; the current flows alternately axially through the conductors and radially through the thermoelectric material (flows in opposite directions in the n and p-legs) where electrical potential is added.

The thermoelectric material is contained only in the straight portions of the heat exchanger tubes. Annular copper tubes of 0.080 in. wall thickness conduct the electricity around the curved U-bend portions connecting the thermoelements, and through the top portions of the heat exchanger tubes, thus connecting the last of the thermoelements to the next tube assembly. The conductor tube extends through the upper non-TE and tube sheet areas to a copper end-strap, which is connected to the next tube assembly either in series or in a parallel arrangement as required. Insulation is placed inside and outside of this conductor tube to insulate the electrical flow and minimize the heat flow across tubes in these areas; this helps to give a maximum amount of heat flow through the thermoelectric material, as desired. This aspect of the design will require some additional fabrication and materials development effort.

The generator output is taken off the end straps by bus bars which carry the electrical current to the inversion and voltage regulation equipment. Careful attention to the bus arrangement is required so that unduly large magnetic fields are not produced. Adequate electrical insulation to reduce losses and provide safety will also be necessary.

8.2 Results and Performance

The results of the thermoelectric generator performance analysis are presented in the Summary of TCR-TE Plant Data, Table 2 in Section 2. The equations and sample calculations are presented in Appendix F. As discussed in Appendix I, lead telluride thermoelectric material properties forecasted to January 1, 1963 were used as the basis for this study.

The overall thermal and thermoelectric performance of a thermoelectric generator is essentially the same as that of an individual "typical" thermoelectric couple. In other words, by obtaining the performance of a "typical" couple and adding its accumulative results, the generator performance is obtained. The voltages and heat flow are additive when the couples are connected electrically in series while the electrical currents are additive by Kirchhoff's Law when the couples are connected in parallel. For these reasons, the average or "typical" couple concept is used in this study to evaluate the performance of the thermoelectric generator.

The gross electrical power produced by the TCR-TE, Case I, generator is 407 KW in the form of 250 volts, 1630 amp. dc power. Thus, a 4.07% plant gross efficiency is attained. This efficiency value represents the percent of reactor core thermal output that is converted to gross electrical power.

The net electrical power output from the TCR-TE, Case I, design is estimated to be 315 KW, which is equivalent to a 3.15% overall net plant efficiency. Figure 3 shows a schematic of the TCR-TE concept, and includes the estimated outputs. The estimated auxiliary power requirements and inversion losses which form the basis for calculating the net plant efficiency are discussed in Section 12.

For the Case I heat exchanger design a total effective thermoelectric tube length of 5525 ft. is required to produce the necessary electrical power. Adding a 4% margin for heat exchanger ineffectiveness and degradation, a total of 5750 ft. of tubing is specified for the final design. This tubing is installed as 640 U-tubes, each with an effective thermoelectric material length of 9 ft. The TE tubes are connected into thirteen parallel paths, thus producing 250 volt, 1630 amp dc power. This number of parallel paths should afford adequate reliability.

The results presented above for the performance of the TCR-TE, Case I plant are based on conditions and assumptions chosen or specified for the reference design. To a certain extent, improvements in these conditions and in design concepts can and should be realized, resulting in related improvements in the plant net efficiency. Some of the possible methods of improving the TCR-TE design in order to achieve higher efficiencies are considered in Appendix G.

A general discussion on thermoelectric generator - reactor system control considerations is included in Appendix D. General thermoelectric generator characteristics are discussed in that Appendix and curves indicating performance capabilities are given. The discussion also includes the effect of load changes on the generator, and how these relate to reactor operation.

9. ELECTRICAL INVERSION SYSTEM - CASE I

9.1 General

In the power and voltage range required for the TCR-TE application, it is conventional to use rotating equipment for inverting DC to AC, primarily because of economic considerations. However, if reliability is a major factor it is desirable to consider inversion equipment with no moving parts. Two types of static systems were considered for this application: the mercury-pool rectifier (IGNITRON), and solid state devices. The former type of system is believed superior for applications of this type within the next five years.

9.2 Recommended System

Westinghouse has considerable experience in the application of IGNITRON static inverter systems in the range of 350 KW to 100,000 KW to obtain variable and high frequency A.C. outputs. In addition, the IGNITRON controlled rectifier has been built by Westinghouse for over 20 years for many applications requiring the unidirectional control of electric current and, as a result, has an established excellence of reliability and efficiency.

Nevertheless, the use of the IGNITRON in an inverter for the TCR-TE System will require some engineering development work on the electrical circuitry. Such engineering development will be required for this application only because a system of this kind has never been specifically applied to this type of D.C. input to produce 60 cps, 3 ϕ 220 V power at a power level of only 300 KVA. Additional quantities of similar devices with power ratings as high as 400 KVA would enjoy an appreciably lower unit cost, since no basic engineering changes in equipment or design would be required.

In view of these facts, and the results of studies of other systems discussed later in this section, an IGNITRON inverter system is recommended in order to obtain the most economical and reliable static inverter system on initial TCR-TE generating units.

9.3 Description of Recommended IGNITRON System

Figures 26 and 27 indicate the proposed schemes of inversion employing high power, high voltage controlled rectifiers of the type available in IGNITRONS.

As shown in Figure 26, the IGNITRON inverter system will include associated switch gear to provide a complete installation, including all control and load protection components customary to an electrical power generating unit.

Table 9 summarizes the general performance data of the proposed system, and Table 10 contains a listing of major components.

BLOCK DIAGRAM OF RECOMMENDED INVERSION SYSTEM

FIGURE 26

E. D. SK. 280432 B

SCHEMATIC OF RECOMMENDED INVERSION SYSTEM

E. D. SK. 280433 B

FIGURE 27

TABLE 9

PERFORMANCE DATA FOR INVERSION SYSTEM

300 KVA Inverter DC to 220 V. 3 ϕ 60 CPS

1. Input: 500 V. maximum based on $175\% \pm 10\%$ open circuit.
100% load DC Volts = 286 Volts $\pm 10\%$.
2. Output: 0 to 300 KVA, 220 V $\pm 5\%$, 3 ϕ 60 ± 1 cps.
Wave form - Sine Wave - 12% Harmonics
Mostly resistive load - approximately 25 HP motor load
3. Circuit - Self-excited Inverter
DC input through suitable inductance commutating capacitors
on AC output. Filter on AC output.
Switching system to switch capacitors and for resistive load
bank to meet output requirements.
4. Efficiency at least 90% at full rated load.

TABLE 10

BILL OF MATERIALS FOR MAJOR COMPONENTS OF INVERSION SYSTEM

- 1 - ISE 36 Inverter Equipment consisting of 6 tubes
- 1 - Set of firing circuit
- 1 - Regulator
- 1 - Approximately 650 KW, 3-phase transformer
- 1 - 400 KVAR Capacitor set
- 1 - Reactor ("Choke"), 1200 amps., 5 millihenrys
- 1 - AC breaker
- 1 - DC breaker
- 1 - L-C filter
- 1 - Resistor assembly

As shown in Figure 26, voltage control is achieved through the use of a simple voltage sensing scheme to switch in resistor load banks as required. This method of voltage regulation is proposed for the TCR-TE prototype plant for the following reasons:

1. The final filter network on the AC output is reduced in weight and complexity as a result of the elimination of excessive input voltage variation during all normal operations.
2. The reactor load can now be considered constant for all normal power range operations.
3. The voltage-regulating resistor bank need not be considered a complete loss in overall efficiency since it can provide directly, without inversion, a secondary source of pure water by powering a distilled water generator (See Section 10 of this report).
4. The possible problems associated with high frequency generator output current variations resulting from variable cutoff cycle voltage control (to achieve non-dissipative voltage regulation) need not be considered or studied as an additional problem in the initial design of the TCR-TE system.

The inverter system will consist of multiple packages that can easily be field connected, for the most part by AN connectors. As presently conceived the largest and heaviest single package will consist of the 650 KW 3-phase transformer listed in the condensed bill of materials (Table 10). This package will measure approximately 60 inches x 25 inches x 45 inches and weigh approximately 3000 lbs. Final designs may show advantages to combining some of the smaller components into a single larger package. The total weight of the inverter system as described is estimated not to exceed 15,000 lbs.

The components expected to require the most maintenance would be the standard switch gear items, such as breakers and contactors. The types of contactors to be employed would be those normally rated for thousands of cycles and the breakers are those normally employed for applications requiring extreme reliability. Standard procedure on these devices calls for an inspection of the contacts after a fault interruption. This procedure is a minimum time operation and generally consists of only a brief visual inspection.

In general, the basic mechanisms to be supplied in the recommended inversion system have service life ratings in excess of 30 years. However, if the breakers were required to interrupt a fault causing

extremely high surge currents the contacts would probably need replacement. Therefore, all such contacts are considered to be the least reliable component and the purchase of a complete set of spare contacts for a two year operation period is recommended. As added insurance for remote locations, a spare set of IGNITRONS might be worth the small additional investment although a need for frequent replacement is not anticipated.

9.4 Alternate Systems Investigated

9.4.1 Transistorized Inverter

Transistors up to a power rating of 25 amps have been used in sufficient quantities to establish typical reliability figures with reasonable accuracy. For the most part these devices have been used for very precise voltage and frequency sources with ratings up to 5 KW, 220 V, 60 cycle. However, if the same design techniques were employed for the power capacity needed in the TCR-TE application, the inversion system would require 576 transistors in each leg of the three-phase output for a total of 1728 transistors having twenty-five ampere ratings. Even if a 99.9% reliability is assumed for each of the many transistors in this system, a totally unacceptable overall reliability would result. Consequently, it appears that this method offers little chance of achieving a reasonable reliability. Even if 100 ampere units were developed, the source voltage would still require nine series-connected bridges of 16 transistors per bridge for each phase, for a total of 432 units.

9.4.2 Solid State Controlled Rectifier

TRINISTOR static power inversion systems are presently being developed by Westinghouse for ratings up to 300 KVA. The successful completion of this effort for applications such as the TCR-TE inversion system depends on many factors.

If a single inverter circuit is used for each phase of the output of the 300 KVA unit, the individual inverter rating must be at least 100 KVA. Assuming an efficiency of 90%, the input power to each inverter will be about 110 KVA. At a voltage input of 300 volts, the inverter must carry approximately 370 amperes. The average TRINISTOR current will be approximately 190 amperes; consequently, a device having a rating of at least 200 amperes should be used. Rather than using a single TRINISTOR, it is possible to specify parallel TRINISTORS or parallel inverters to permit using devices with lower ratings.

The inverter must be designed to support the maximum available input voltage. Devices having ratings of 200 to 400 volts are currently available, and development of higher voltage devices is currently under way. A series-connected pair of TRINISTORS has been used successfully to increase the input voltage rating of such inverters. Across each TRINISTOR a resistor is used to balance the voltage when the device is not conducting. The additional loss produced by these resistors is small and normally does not exceed 0.5% of the output power. A resistor-capacitor-diode network has also been used in the circuit to limit the rise time of the applied voltage to prevent uncontrolled breakdown.

In summary, circuitry for providing high power inverter circuits has been developed and operated successfully. The TRINISTOR voltage and current ratings required for a 300 KVA system are feasible. Using currently available devices, a high power system can be constructed; however, higher rating devices will provide a system having fewer components and greater reliability.

9.5 Bases for Selection of IGNITRON System

The selection of the IGNITRON System for the TCR-TE prototype plant is based on the following considerations:

1. IGNITRON circuitry design involves no requirements for improving the state-of-the-art so that the major purpose of the project, the development of a TE generator, could not be confused or complicated by the need for plant component developments of secondary importance.
2. The cost of an IGNITRON System for this application can be estimated within normal engineering tolerances. This is not possible on systems requiring research and development to advance the state-of-the-art.
3. Even though reasonably well established solid state devices such as transistors or TRINISTORS are available for lower power and voltage ranges, the required multiplication of series and parallel elements to the conditions imposed by the TCR-TE application considerably reduces the overall reliability, as well as requiring development of protective circuits.
4. IGNITRONS are designed to operate at considerably higher voltages than those specified in the present TCR-TE application, while solid state devices are currently limited to lower operating voltages. As TE generator insulation materials and design techniques improve with advancements in the technology, operating output voltages will rise markedly in order to improve overall efficiencies. Hence, the use of IGNITRONS would allow operating conditions which give higher efficiencies.

10. AUXILIARY SYSTEMS - CASE I

10.1 General

Although an ideal Case I TCR-TE system would consist only of a nuclear reactor with integral thermoelectric elements and a TE cold water supply, a practical system requires auxiliary equipment to support its operation. The TCR-TE auxiliary systems have been designed to be as simple as possible consistent with periodic refueling, full power maintenance, water treatment requirements, long life, accessibility and pressurizer control considerations. Simplification for totally unmanned operation would require a revised set of conditions beyond the scope of this study. The basic TCR-TE concept is considered a first step toward ultimately unmanned operation by replacement of the rotating turbine-generator with static thermoelectric elements.

The auxiliaries discussed in this section include: reactor coolant system, chemical and volume control system, safety injection system, sampling, and secondary coolant system. The auxiliaries will be located in two separate modules - the "auxiliary module", containing the bulk of the equipment and a small "radioactive auxiliary module", containing auxiliary components which are expected to accumulate a significant amount of radioactivity during their lifetime. Figures 28, 29 and 30 illustrate the general arrangement for the auxiliary systems.

Table 11 lists the pressure, temperature, flow and level instrumentation required for Figures 28, 29 and 30.

Tables 12, 13 and 14 list the Case I auxiliary system pumps, heat exchangers, and tanks and demineralizers, respectively.

The auxiliary module will be located adjacent to the reactor module and will be accessible at all times. The small radioactive auxiliary module will be shielded and located in the area of the reactor.

The following sections describe the functions and equipment for the major auxiliary systems.

10.2 Reactor Coolant System

The reactor coolant system, by definition, includes the main coolant loop and the pressure control system. Since the main coolant loop is not considered part of the auxiliary systems and is covered elsewhere, this section will describe the pressure control functions and equipment.

TCR-TE AUXILIARY SYSTEM SCHEMATIC
FIGURE 28

TCR-TE PROPOSED SECONDARY COOLANT SYSTEM - CASE I

FIGURE 30

TABLE 11PROCESS INSTRUMENTATION FOR AUXILIARY SYSTEMS

<u>Item</u>	<u>Description</u>
PRC-1	Pressure Recording Control - Controls Pressurizer Power Operated Relief Valve and Adjusts Pressurizer Heater Current
PRC-2	PRC-1 Backup - Operates PA-3 and Scram
PA-3	Pressure Alarm for PRC-2
PC-4	Pressure Control - Liquid Phase Pressure, Operates PA-5 and Scram
PA-5	Pressure Alarm for PC-4
PRC-6	Low Pressure Tank Pressure and Operates PA-7
PA-7	Pressure Alarm for PRC-6
PI-8	Pressure Indicating - N ₂
PI-9	Pressure Indicating - H ₂
PCV-10	Pressure Control Valve - N ₂
PCV-11	Pressure Control Valve - H ₂
PI-12	Pressure Indicating - Decay Heat Pump Discharge
PI-13	Pressure Indicating - Shield Water Demineralizer
PI-14	Pressure Indicating - Component Cooling Pump Discharge
PI-15	Pressure Indicating - Transfer Pump Discharge
PI-16	Pressure Indicating - Screen Outlet - Secondary Loop
PI-17	Pressure Indicating - Filter Outlet - Secondary Loop

TABLE 11 (Cont'd)

<u>Item (Cont'd)</u>	<u>Description (Cont'd)</u>
TCR-1-1 thru 10	Temperature Recorder - Multipoint Recorder for Monitoring Plant Temperatures
TR-1-1	Pressurizer Discharge
TR-1-2	Non Regenerative Heat Exchanger Discharge
TR-1-3	Low Pressure Tank
TR-1-4	Mixed Bed Demineralizer Discharge
TR-1-5	Pressurizer
TR-1-6	Main Coolant - Cold Leg
TR-1-7	Main Coolant - Hot Leg
TR-1-8	Shield Water Cooler Outlet; Also Operates TA-6
TR-1-9	Secondary Loop Inlet
TR-1-10	Secondary Loop Outlet
TI-2	Temperature Indicating - Decay Heat Exchanger Inlet
TI-3	Temperature Indicating - Decay Heat Exchanger Outlet
TI-4	Temperature Indicating - Cooling Water Discharge, Decay Heat Exchanger
TI-5	Temperature Indicating - Shield Water Cooler Inlet
TA-6	Temperature Alarm - Shield Water Cooler Outlet
TI-7	Temperature Indicating - Shield Water Demineralizer
TCV-8	Temperature Control Valve - Self Actuated Temperature Regulation of Cooling Water to Non-Regenerative Heat Exchanger
TCV-9	Temperature Control Valve - Three-way Bypass Around Demineralizer
HC-1, HC-2	Hand Control - Remote Stop Valves for Shutdown Cooling System
HC-3	Hand Control - Remote Valve for Boric Acid

TABLE 11 (Cont'd)

<u>Item (Cont'd)</u>	<u>Description (Cont'd)</u>
HIC-1	Hand Indicating Control - Remote Manual Throttling Valve in Pressure Letdown System
HIC-2	Hand Indicating Control - Remote Manual Makeup Water Valve
FI-1	Flow Indicating - Letdown Flow Rate
FI-2	Flow Indicating - Decay Heat System
FIC-3	Flow Indicating Control - Component Cooling Pumps Discharge; Also Operates FA-4
FA-4	Flow Alarm - Component Cooling Pumps Discharge
FIC-5	Flow Indicating Control - Secondary Loop
LRC-1	Level Recording Control - Records Pressurizer Level and Operates LA-2
LA-2	Level Alarm - Pressurizer
LIC-3	Level Indicating Control - Low Pressure Tank; Also Operates LA-4
LA-4	Level Alarm - Low Pressure Tank
LI-5	Level Indicator - Backup for LRC-1 on Pressurizer
LIC-6	Level Indicating Control - Pure Water Storage Tank; Also Operates LA-7
LA-7	Level Alarm - Pure Water Storage Tank
LA-8	Level Alarm - Resistor Bank Tank
LG-10	Level Gauge - Shield Water Expansion Tank
LA-11	Level Alarm - Shield Water Expansion Tank
LA-12	Level Gauge - Water Storage Tank
LA-13	Level Alarm - Water Storage Tank

TABLE 12

TCR-TE AUXILIARY SYSTEM PUMPS - CASE I

<u>Function</u>	<u>No. Req'd</u>	<u>Type</u>	<u>Rated Flow</u> (gpm)	<u>Normal Head</u> (psi)	<u>Design Press.</u> (psig)	<u>Design Temp.</u> (°F)	<u>Motor HP</u>	<u>Approx. Input</u> (KW)
Charging	2	Pos.. Displ.	2(each)	1150	1500	200	3.0(each)	2.0(each)
Makeup & Transfer	1	Cent.	7.5	20	50	200	.25	.14
Decay Heat	1	Cent.	25	50	200	350	1.5	1.2
Component Cooling	2	Cent.	65(each)	35	50	150	3.0(each)	2.0(each)
Water Storage Transfer	1	Cent.	70	35	50	200	3.0	2.2
Shield Water Demineralizer	1	Cent.	5	15	50	150	.13	0.1
Chemical Transfer	1	Cent.	7.5	20	50	200	.25	.14
Secondary Water	5	Cent.	200(each)	50	100	200	7.0(each)	5.0(each)

107

TABLE 13

TCR-TE AUXILIARY SYSTEM HEAT EXCHANGERS - CASE I

<u>Function</u>	<u>No. Req'd</u>	<u>Heat Loads (Btu/hr)</u>		<u>Design Flow</u>		<u>Design Pressure (psig)</u>		<u>Design Temp. (°F)</u>	
		<u>Normal</u>	<u>Design</u>	<u>Tubes</u>	<u>Shell</u>	<u>Tubes</u>	<u>Shell</u>	<u>Tubes</u>	<u>Shell</u>
Regenerative	1	1.58×10^5	1.58×10^5	500 lb/hr	500 lb/hr	1500	1500	600	600
Non-regenera- tive	1	1.92×10^5	3.84×10^5	1000 lb/hr	40 gpm	1500	75	600	200
Decay Heat	1	0	7.45×10^5	25 gpm	40 gpm	200	75	350	200
Shield Core	1	4.20×10^5	4.20×10^5	44 gpm	-	50	-	150	-
Air Cooled Condenser (Pure water)	1	0 to 5.12×10^5	5.12×10^5	0 to 530 lb/hr	Natural Convection	Ambient	Ambient	220	180
Shield Water Air Coolers	4	6.15×10^5 Total	6.15×10^5 Total	65 gpm Total	2.5×10^4 cfm total	35	Ambient	150	150

TABLE 14TCR-TE AUXILIARY SYSTEM TANKS AND DEMINERALIZERS - CASE I

<u>Function</u>	<u>No. Req'd</u>	<u>Size Cu. ft.</u>	<u>Design Press. (psig)</u>	<u>Design Temp. (°F)</u>	<u>Dimensions</u>
Low Pressure	1	30	50	250	7' x 2' 6" dia.
Pure Water Storage	1	60	50	250	7' x 3' 6" dia.
H ₂ flask	1	0.2	3000	200	12" x 7" dia.
Chemical Control	1	1	25	200	18" x 12" dia.
Boric Acid	1	1	25	200	18" x 12" dia.
Water Storage	1	1200	35	150	24' x 8' dia.
Expansion	1	1.6	25	200	24" x 12" dia.
Shield Demineralizer	1	4	50	150	5' x 12" dia.
Purification Demineralizer	1	8	50	150	5' x 18" dia.
Resistor Bank	1	30	50	250	7' x 2' 6" dia.
Weir	1	30	25	150	3' x 3' x 3' 4"

10.2.1 Pressure Control

The pressure control system performs the following functions:

1. It maintains a desired level of pressure in the main coolant loop during steady state operations.
2. It places limits on the pressure variations which result from main coolant volume changes occurring during power plant load transients.
3. It prevents the pressure in the main coolant system from exceeding design values during abnormal operating conditions.

The pressure control system consists of the following equipment:

1. A pressurizer vessel of the required volume, integral with and forming the upper portion of the reactor vessel. The five top mounted control rod drive mechanisms are mounted in the central portion of the pressurizer.
2. Replaceable immersion-type heaters.
3. A spray system.
4. Code safety valves.
5. Remotely operated relief valves.
6. Interconnecting piping and valves.
7. Pressure, level and temperature instrumentation.

The pressurizer vessel is sized to accommodate all main coolant volume surges which occur during allowable plant load transients (approximately 26% of main coolant volume).

Enough water is maintained in the pressurizer to keep the heaters, mounted near the bottom, fully immersed at all times. Saturated steam and entrapped gases are confined to the spaces above the water. During normal operation, the input power to the heaters is automatically adjusted by instrumentation to maintain a specified pressure.

The neck between the pressurizer and the main cylindrical section of the heat exchanger contains a series of metal plates with stagnant water between, forming an effective insulation

barrier between the main coolant water and pressurizer water. The five control rod drive mechanisms pass through the plate assemblies, with about .050" clearance being allowed between the control rod drive mechanisms and the adjacent cylindrical holes through the plates. This clearance is provided for control rod drive mechanism expansion and contraction.

During transient operation, expansion or contraction of the main coolant occurs. Upon expansion, water flows from the reactor vessel through an external pipe and check valve to the upper end of the pressurizer (See Figure 28) where it is sprayed into the steam above the water in the pressurizer. The spray condenses part of the pressurizer steam, thus relieving the pressure and accommodating the excess water. Upon contraction of main coolant water, water flows from the pressurizer through a second external pipe and check valve into the reactor vessel to compensate for the contracted coolant. At the same time a portion of the remaining water in the pressurizer evaporates, resulting in a temporary decline in temperature and pressure. The heaters are then automatically energized to increase the pressure to its normal value.

Variations of the level in the pressurizer are noted by instrumentation. An alarm is sounded in the control room when certain limits are exceeded. Pressurizer level is manually controlled.

Code safety valves and a remotely operated relief valve are provided for further protection of the plant. The discharge from the pressurizer safety and relief valves is directed to the low pressure tank where it is quenched and cooled.

10.3 Chemical and Volume Control System

The chemical and volume control system includes the following sub-systems:

1. Charging and Purification
2. Water Make-up
3. Chemical Control
4. Vent and Drain

10.3.1 Charging and Purification System

The charging and purification system (Figure 28) performs the following functions:

1. It maintains the concentration of main coolant water impurities at a desired low value.
2. It allows the introduction of a borated solution for emergency backup of control rods.
3. It allows the introduction of corrosion inhibiting chemicals to the main coolant water.
4. It provides a means for removing non-condensable gases from the main coolant water
5. It provides pumping capacity for the safety injection system.
6. It is used to control the proper water level in the pressurizer.
7. It provides a means for filling the main coolant system following refueling or maintenance operations.

The charging and purification system consists of the following equipment:

1. Regenerative heat exchanger
2. Non-regenerative heat exchanger
3. Pressure letdown valve
4. Demineralizer
5. Low pressure tank
6. Two-speed charging pumps

The two heat exchangers reduce the temperature of the water bled from the primary system to insure against flashing following pressure letdown and to avoid thermal damage to the demineralizer resins. The regenerative heat exchanger partially recovers the heat rejected by the bled water as it is returned to the primary system.

The pressure letdown valve allows the operator to regulate the flow of water bled from the main coolant system and reduces the pressure to a value corresponding to that in the low pressure tank. During normal plant operation, one of the charging pumps is operated so that its output matches the pressure letdown valve outflow, thus maintaining the primary loop coolant volume and pressurizer level at a constant value.

The disposable mixed bed demineralizer unit purifies the reactor coolant. Protection against high temperatures is provided by a temperature controlled by-pass valve.

The low pressure tank has the following functions:

1. It serves as a coolant reservoir and surge tank.
2. It receives hydrogen injected into the primary coolant and provides for O₂ control.
3. It receives the steam discharge from the pressurizer relief valves.
4. It provides a means of removing non-condensable gases from the primary coolant.
5. It provides a means of sampling the primary coolant for radioactive gas buildup.

Two high-pressure, positive displacement charging pumps are provided to return the purified coolant into the main coolant system.

There are three principal modes of operating the charging and purification system - normal plant operation, operation during plant shutdown, and operation during plant startup. During normal plant operation, water is bled continuously from the cold leg of the reactor vessel. The water passes through the regenerative and non-regenerative heat exchangers, through the pressure letdown valve, through the demineralizer and into the low pressure tank through the inlet spray ring. After absorbing corrosion-inhibiting hydrogen in the tank, the water passes through the charging pumps, the regenerative heat exchanger and thence back to the reactor vessel. For plant shutdown, the pressure and temperature of the primary coolant must be reduced from the operating level to a much lower value by the use of the shutdown cooling system. During this time, water is supplied to the primary coolant system by the charging and purification system, to provide make-up for main coolant contraction. During plant startup, excess coolant, resulting from expansion as the plant temperature is increased, is bled through the pressurizer and is removed through the charging and purification system to the waste disposal system.

10.3.2 Water Make-up

Make-up water for the primary system may be obtained from several sources, depending on plant location and local water purity. Assuming ideal water source conditions, the water from the secondary coolant loop can be diverted to a pure water storage tank for primary system makeup use as required, or else supplied directly.

Since ideal water conditions can not be assured, make-up water will be supplied from two sources. The first is a tap off the shield water demineralizer loop to the pure water storage tank. The second source is provided by diverting a part of the secondary coolant loop water through an evaporator-condenser system, as shown in Figure 28. The diverted water will first pass through a weir tank, then into the evaporator tank. This evaporator is heated by the resistor bank which provides voltage regulation for the output of the TE generator and inverter combination. The water is boiled at atmospheric conditions, condensed in finned tubes, and finally passed to the pure water storage tank.

As plant load drops below maximum, the TE output voltage rises, causing a load rise on the resistor bank. The excess heat caused by the load rise on the resistor bank is thus utilized to provide a second source of make-up water, by evaporation. The resistor bank power input can vary from approximately 315 KW to 0 KW, depending upon site power loads. The condenser has been sized for a maximum of 150 KW. Any excess steam will be vented.

10.3.3 Chemical Control

The chemical control system, shown in Figure 28, provides borated water for emergency reactivity control by injecting a neutron absorbing solution into the primary coolant system in the unlikely event of control rod failure. This system has the capacity to inject sufficient borated water for the complete shutdown of the reactor. Startup, normal operation and shutdown control of the reactor, except under emergency conditions, is accomplished by insertion or withdrawal from the core of the neutron absorbing control rods with their fuel-bearing followers.

Additional functions of the chemical control system are:

1. It provides reactor coolant pH control.
2. It provides H₂ for O₂ control.
3. It provides borated water for initial operation of the safety injection system.

4. It provides N_2 for overpressure and purging of the low pressure tank.

The chemical control system equipment consists of mixing and storage tanks, a pump, and necessary piping, valves and instrumentation.

10.3.4 Vent and Drain System

Vents and drains are provided at suitable locations for discharging radioactive fluids and gases to the collecting tank of the waste disposal system.

10.4 Auxiliary Coolant System

The auxiliary coolant system includes the following sub-systems:

1. Component Cooling
2. Shutdown Cooling
3. Decay Heat Removal
4. Spent Fuel Storage

10.4.1 Component Cooling System

During normal operation, the component cooling system (See Figure 29) provides for the removal of the heat from the neutron shield tank and spent fuel storage tank, and associated heat exchangers. During shutdown, this system provides for the removal of decay heat. The system consists of three basic loops as follows:

1. A shield water cooling loop containing four air blast coolers and an expansion tank, component cooling pumps, with related piping, valves, and instrumentation. Also included in this loop is the cold side of the main coolant loop, non-regenerative heat exchanger and the decay heat exchanger.
2. A shield water demineralizer loop consisting of a centrifugal pump, a mixed bed demineralizer, and related piping, valves and instrumentation.
3. A refueling water storage tank loop with transfer pump, related piping, valves and instrumentation.

10.4.2 Shutdown Cooling System

The shutdown cooling system dissipates residual heat produced in the irradiated core immediately following a plant

shutdown by continuing to circulate secondary coolant water through the TE tubes. It is kept in operation until the primary system pressure and temperature have fallen sufficiently to allow the decay heat removal system to be placed in service. When the decay heat removal system is put into operation, use of the shutdown cooling system is discontinued. This system consists of the secondary coolant water loop, a pump, and related piping, valves and instrumentation.

10.4.3 Decay Heat Removal System

The decay heat removal system is used, during activities such as fuel replacement, to remove decay heat generated by the fission products in the reactor core. During such a period, the reactor vessel head may be removed from the vessel. The decay heat removal system is put into operation after the shutdown cooling system, previously described, has been used a few hours to reduce the primary coolant system pressure and temperature. The decay heat removal system continues to operate for the duration of the shutdown. This system consists of a decay heat exchanger, pump, valves and related instrumentation.

10.4.4 Spent Fuel Storage System

A spent fuel storage tank is provided adjacent to the reactor vessel-TE heat exchanger shield water tank for storage of spent fuel until it can be removed for shipment to a reprocessing plant. Cooling is provided as noted in Section 10.4.1. The spent fuel is stored in racks in a subcritical arrangement.

10.5 Safety Injection System

A safety injection system is provided to keep the reactor core covered with water, preventing core meltdown, in the unlikely event of an accident involving a loss of coolant from the primary system. The system, initially energized by the plant operator as a result of alarms indicating rapidly falling pressurizer level and pressure, operates to inject water through the charging pumps into the central chimney above the core inside the reactor vessel.

10.6 Sampling System

Permanently installed sampling lines are provided to sample remotely fluids from the following locations:

1. The inlet header of the purification system demineralizer.
2. The outlet header of the purification system demineralizer.

3. The low pressure tank to check pressurizer discharge gases.

Sampling is also performed directly at the following locations:

- a. The non-radioactive side of all heat exchangers where heat is transferred from radioactive fluids.
- b. All waste disposal system tanks.
- c. The spent fuel storage pit.

A sampling and analysis cubicle is provided with a ventilation hood, drain sink, benches, radiation counting devices, and basic analytical equipment.

10.7 Secondary Coolant System

The secondary coolant system provides water for use on the cold side of the thermoelectric tubes. Ideally, this system would consist of a pump and related piping, valves and instrumentation. In actual practice, water treatment may be required to minimize fouling of the heat transfer surfaces, pitting and stress corrosion. The amount of treatment will vary depending on water conditions at the particular site chosen so that no finalized system can be defined at this time. Assuming reasonably good water conditions (40 ppm of solids), it is possible that only an in-line replaceable filter or a screen will be required. Under poor water conditions (greater than 300 ppm of solids), a screen, in-line filter and mixed bed demineralizer may be required. The frequency of screen and filter replacement, demineralizer regeneration and tube clean-up will vary with local water conditions. An alternate arrangement is a periodic flushing of lines with chemical solutions. Until experience in this area is gained, replacement and clean-up during maintenance periods should be planned. A research and development program on secondary system fouling and cleaning is recommended elsewhere in this report.

Three different fouling factors have been considered in making thermal-hydraulic calculations (0, .007 and .0011), because of lack of precise knowledge of the site water conditions. The major effect of the factor chosen is illustrated by Figure 18. For a clean secondary system (secondary system fouling factor $r_f = 0$) the net plant efficiency will be 3.64%. For a secondary system r_f of .0011, the net plant efficiency will be reduced to 2.88%, showing the direct effect on net plant efficiency caused by varying fouling factors. Clean-up of water by filters and demineralizers does not necessarily insure that the fouling factor will be zero or near zero. Certain types of clean water can foul at a more rapid rate than certain types of dirty water, since fouling is partially a function of the types of impurities and the types of impurities will vary from location to location.

If a reasonably clean water source is assumed, the secondary coolant system would consist of the following equipment:

1. A wire mesh inlet screen to remove gross particles.
2. A pump to give the required coolant flow (25 KW).
3. An in-line filter to remove suspended solids.
4. Related piping, valves and instrumentation.

A system of this type is included in Figure 30 .

10.8 Waste Disposal

The preliminary design of a waste disposal system for removing radioactive wastes from the plant will be dependent upon site conditions and has not been detailed for this study.

A typical waste disposal system receives and processes all liquid, gaseous and solid radioactive wastes from the plant. The gases are collected, processed, held, diluted, and then discharged through a stack on a schedule dependent upon meteorological conditions. Liquids are processed to remove radioactive impurities. The impurities are allowed to decay a suitable length of time prior to dilution and discharge or are concentrated and stored at the plant site. Solid radioactive wastes are placed in underground tanks or in shielded containers for disposal by burial.

11. NUCLEAR INSTRUMENTATION - CASE I

11.1 General

The TCR-TE nuclear instrumentation (Fig. 31) includes two channels which monitor neutron flux and reactor start-up rate during start-up and operation. Because of the wide range of nuclear activity in a reactor core, each channel employs two neutron detectors which cover overlapping portions of the power spectrum defined as the source, intermediate, and power ranges, respectively.

11.2 Source Range

The source range consists of a BF_3 proportional counter, pulse integrator, power supply, log amplifier, rate amplifier, level indicator and period indicator.

The pulse signal from the BF_3 detector is fed to the pulse amplifier. This unit amplifies the signal and discriminates to eliminate noise and gamma signals. The signal is then fed to the log amplifier which integrates the pulses and converts the pulse into an output proportional to the logarithm of the number of pulses. The logarithmic signal is fed to the level indicator. In addition, the logarithmic signal is differentiated and amplified providing a signal for the start-up rate indicator.

When reactor power is above the range of the BF_3 counter, the high voltage to the counter is cut off manually.

11.3 Intermediate Range

The intermediate range system utilizes a compensated ion chamber in conjunction with the source range log and rate amplifiers.

The output of the compensated ion chamber is a current proportional to power level. (Gamma background is cancelled out by the compensation). The current output is fed to the same log amplifier used for the source range, which converts the linear d-c input to an output proportional to the logarithm of the input. The remainder of the channel is the same as that used for the source range. The logarithmic amplifier is manually switched between source range and intermediate range in the overlap region between the two ranges.

11.4 Power Range

The power range consists of a linear amplifier and level indicator used in conjunction with the intermediate range compensated ion chamber. The ion chamber output current (proportional to power level) is fed to

TCR-TE

NUCLEAR INSTRUMENTATION SYSTEM

FIGURE 31

E. D. SK. 280387 B

the power range amplifier and then to an indicator. The detectors are housed in thimbles installed outside the water shield tank, as shown in Figure 15. A recorder is provided with a four position switch to select the output of either log amplifier or power range amplifier.

A test panel is used to check the pulse, d-c level, and period signals. Signals are provided to the rod control system to give an indication of high start-up rate and high neutron flux level.

11.5 Radiation Monitoring

In view of the intended isolated location of the plant, and the desire to maintain low cost, a minimum of radiation monitoring, consistent with plant safety, is provided. Figure 32 is a block diagram of the radiation monitoring system. To maintain plant safety the component cooling water and secondary water are monitored for radioactivity. This equipment will detect a leak from the primary system to these auxiliary systems.

The component cooling system is a closed system and, therefore, the activity from small leaks will buildup over a period of time to a detectable level. Because the secondary system is a once-through system, the secondary system monitor will detect only those leaks that result in a detectable activity on the first pass by the monitor. Smaller leaks can be detected by sampling.

Due to the limited size of the crew maintaining the plant, it is believed that portable monitors are the best choice for health protection. This will permit the use of a few portable monitors to serve in place of the several fixed monitors which would be used in a conventional nuclear power plant.

TCR-TE
RADIATION MONITORING SYSTEM

FIGURE 32

E. D. SK. 280386 B

12. PLANT OPERATION - CASE I

12.1 General

This section of the report covers cold startup, normal plant operation, transient considerations, shutdown, and refueling.

12.2 Cold Startup

The recommended cold startup procedure is based on the following assumptions:

1. Core and internals are installed.
2. Thermoelectric heat exchanger and pressurizer are installed.
3. Reactor vessel is filled with water and pressurizer is 1/4 full.
4. Diesel plant is operating.

An outline of the cold startup procedure follows:

1. Check water chemistry and add chemicals to water supply, if required.
2. Turn on pressurizer heaters at part load (23 KW). Assume a starting water temperature of 50°F and a heating rate of approximately 75°F per hour. The water is to be heated to approximately 212°F, holding water level constant. Vent air remaining in pressurizer after water boils. (2.5 hours).
3. Make final instrumentation, control and rod mechanism check-offs. Check inverter equipment and secondary loop pump, instrumentation and valves. (0.5 hr. during Item 2 time).
4. Take reactor to criticality. With reactor critical, increase reactor power level to provide a primary coolant heating rate of approximately 75°F per hour. At the same time, pressurizer heater input is to be reduced to approximately 11 KW, giving a pressurizer heating rate of approximately 37°F per hour. Also at the same time as reactor power level is increased, the secondary coolant loop pumps are to be turned on to give a secondary coolant flow of approximately 300,000 lb/hr at 15 KW pump input. The main coolant heating is continued until approximately 300°F temperature is reached. As main coolant heating is continued, the pressurizer heating is also continued at a slightly greater rate. (3.5 hours).

5. When the main coolant temperature is approximately 300°F, enough power will be available from the thermoelectric generator to permit a gradual increase in the pressurizer heating rate and the secondary coolant loop flow. At this point, the thermoelectric generator output will be additive to the diesel generator output. Reactor heating and pressurizer heating are continued until the main coolant temperature reaches 525°F average.

At the appropriate time, the component cooling pumps, the shield water cooling fans and sump pump must be turned on. (3 hours).

6. The system is now ready for full power.

Total time zero to full power - 9 hours.

Table 15 shows an estimated breakdown of the maximum auxiliary power requirements for a cold startup. Totals of the requirements have not been shown because the maximum load will be considerably less than the sum, since loads will be sequenced in accordance with the cold startup procedure. This requirement will be supplied by the auxiliary diesel-generator set until the thermoelectric-generator inverter power output is sufficient to allow switching the loads sequentially from the diesel-generator set to the thermoelectric-generator inverter output. It is estimated that a 40 KW diesel generator set will supply sufficient power for the starting sequence.

Alternate startup schemes, such as a "solid water" sequence outlined in Reference 3, are possible. However, none of the alternates appear to give a better balance of low installed auxiliary power combined with a reasonable overall starting time. If a minimum starting time is the most important criterion, the times shown in the starting procedure could be reduced considerably at the expense of increased diesel generator capacity.

12.3 Normal Operation

During normal operation, the reactor is essentially self regulating. The control rods are periodically adjusted manually to compensate for fuel burnup. Based on work completed under the TCR study, Reference 3, it is expected that the TCR-TE system can accept a 100% electrical load drop (external to the plant system) without scram or control rod motion owing to inherent reactor characteristics and a dissipating heat type of voltage regulator. However, a transient study should be undertaken as a part of the final design. The primary system pressure is automatically controlled by the pressurizer heater control. Neutron flux density, temperature, pressure, and pressurizer water level are automatically monitored. Alarms are sounded and automatic scram is initiated if any of these parameters should vary outside the desired limits.

TABLE 15

TCR-TE MAXIMUM STARTUP LOAD - CASE I
(Individual Values Are Not Additive)

<u>REACTOR SYSTEMS</u>	<u>MAXIMUM KW</u>
Vital Power Bus	3.0
Control Rods	1.0
Pressurizer Heaters	46.0
Charging Pumps	4.0
Component Cooling Pumps	4.0
Sump Pumps	1.0
Makeup and Chemical Pumps	2.0
 <u>SECONDARY SYSTEM</u>	
TE Cooling Loop Pumps	25.0
Inversion Power Losses	40.7
 <u>BUILDINGS AND FACILITIES</u>	
Air Compressor	1.0
Lighting	2.5
Power Outlets	0.7
Heating and Vent Fans	4.5

Table 16 shows a breakdown of the estimated auxiliary power requirements for normal plant operation. Where component operation is intermittent, such as pressurizer heaters, an average value has been used based on expected load factors.

This table shows that a normal operational auxiliary power load of 91.7 KW is expected, of which 18.2 KW are for reactor auxiliaries, 65.7 KW are for the secondary system, and 7.8 KW are for the hotel load. This requirement is supplied by the thermoelectric generator and inversion equipment.

12.4 Transient Operation

An extended analysis of the TCR-TE reactor transient behavior was not considered necessary to the purposes of this preliminary study. Transient load disturbances to the reactor during normal operation will be essentially eliminated through the use of a dissipative type voltage regulator. In addition, dynamic characteristics of the thermoelectric elements have not been defined sufficiently at this time to warrant complete transient studies. (See Appendix D).

Previous studies of the TCR system, while not directly applicable to the TCR-TE plant, do however give a good indication of the behavior that can be expected of the latter. The principal characteristics demonstrated in the TCR study (Reference 3) were inherent plant stability, load following ability with a highly damped response, and sensitivity to voids in the core. The TCR-TE plant has been designed around the same core, operating with essentially the same conditions of temperature, pressure, power, and flow, and with the same ratio of pressurizer steam volume to primary water volume as TCR. The principal differences in dynamic behavior should result from the substitution of a thermoelectric heat exchanger for the conventional steam generator, and from the fact that the primary water volume is half again as great as for TCR. The effect of these changes is expected to be toward more stable, and somewhat more sluggish operation.

As demonstrated in Appendix D, a complete loss of electrical load (including that provided by the voltage-regulating resistor bank) to the thermoelectric generator results in a loss of only 26% of the heat load on the primary. The response of TCR to a similar loss of load (22%) without control rod action, is shown in Figure 33. This shows a characteristic initial rise in reactor power, due to an initial rise in pressure, followed by a decrease in power caused by a deceleration of coolant flow, and later by a rise in core inlet temperature. Coolant temperature must rise in order to maintain constant coolant density in the core as local boiling void decreases, so that in the steady state the pressure has risen by 150 psi.

TABLE 16

TCR-TE AUXILIARY POWER LOAD
DURING NORMAL OPERATION

<u>REACTOR SYSTEMS</u>	<u>AVERAGE KW</u>
Vital Power Bus	2.0
Control Rods	1.0
Pressurizer Heaters	3.8
Charging Pumps	1.0
Component Cooling Pump	2.0
Sump Pumps	0.2
Makeup and Chemical Pumps	0.2
Shield Water Cooling Fans	8.0
	<hr/>
Sub Total	18.2
 <u>SECONDARY SYSTEM</u>	
TE Cooling Loop Pumps	25.0
Inversion Power Losses	40.7
	<hr/>
Sub Total	65.7
 <u>BUILDINGS AND FACILITIES</u>	
Air Compressor	0.1
Lighting and Battery Charger	2.5
Power Outlets	0.7
Heating and Vent Fans	4.5
	<hr/>
Sub Total	7.8
	<hr/>
TOTAL	91.7 KW

TCR RESPONSE TO LOSS OF LOAD
FULL POWER = 9.4 MWt
2 MWt LOAD REJECTION, NO CONTROL

FIGURE 33

E. D. SK. 280464 B

THE 1010

The response of TCR-TE will be similar to that of TCR, though on a slower time scale. One result of the conversion to thermoelectric generation, however, is that an increased primary temperature following loss of electrical load results in an increased heat loss to the secondary coolant. Thus although a complete loss of electrical load (including resistor bank) would yield a 26% loss of thermal load at constant primary temperature, it will actually mean a load loss of less than 26% (but greater than 17%) due to the necessary increase in primary temperature. The associated pressure rise would be less than 150 psia.

During normal operation the primary temperature will drift due to fuel burnup and changes in fission product concentration; this will be corrected periodically by manual operation of control rods.

12.5 Shutdown

During a normal shutdown, the plant output load is steadily reduced to zero and the reactor is taken subcritical. The secondary coolant loop flow is maintained at a rate sufficient to remove the system heat and prevent boiling in the thermoelectric tubes. Decay heat produced in the core will initially maintain the primary system at temperature and pressure and the reactor may be held at hot standby.

As the core decay heat decreases, the system temperature and pressure will also decrease until the decay heat removal system can be put into operation and the secondary coolant loop flow stopped. The auxiliary diesel will provide electrical power during this period.

During a loss of external electrical load, the dissipating heat type of voltage regulator will absorb the thermoelectric generator output so that the reactor system will not "feel" any change of load. The reactor core can then be made subcritical manually, if desired.

During a period of high radiation level, an alarm is sounded and automatic scram is initiated if a preset limit is exceeded.

In the case of a loss of secondary coolant flow, the reactor system temperature and pressure will rise momentarily because the heat sink has been removed. The reactor will then move toward subcriticality because of the core negative temperature coefficient. At the same time, the increased pressure will actuate the automatic high pressure scram system.

The auxiliary loads expected during emergency shutdown, extended shutdown and plant erection will be less than the cold startup load and, therefore, will not affect the auxiliary diesel power requirements. Table 17 shows the maximum estimated emergency shutdown, extended shutdown and plant erection loads.

TABLE 17

TCR-TE SHUTDOWN AND ERECTION LOADS - CASE I

	<u>Max. Emergency Shutdown Load (KW)</u>	<u>Normal Extended Shutdown Load (KW)</u>	<u>Max. Plant Erection Load (KW)</u>
<u>REACTOR SYSTEMS</u>			
Decay Heat Pump	--	1.2	--
Vital Power Bus	1.5	1.5	--
Control Rods	--	--	--
Pressurizer Heaters	--	--	--
Charging Pumps	4.0	--	--
Component Cooling Pumps	1.2	1.2	--
Sump Pumps	0.2	0.2	0.5
Makeup and Chemical Pumps	1.0	1.0	--
Air Blast Fans	--	2.0	--
<u>SECONDARY SYSTEMS</u>			
TE Cooling Loop Pump	15.0	10.0	--
Inversion Power Losses	--	--	--
<u>BUILDINGS AND FACILITIES</u>			
Crane	--	--	0.5
Air Compressor	--	0.3	0.5
Lighting & Battery Charger	1.5	2.5	6.0
Power Outlets	0.7	5.2	11.5
Heating & Vent Fans	--	3.0	4.5
Estimated Total	25.1 KW	28.1 KW	23.5 KW

12.6 Refueling

12.6.1 General

A refueling tank of dimensions identical to the main reactor vessel shield water tank is located adjacent to the shield water tank. An open canal between the two tanks extends from the top of the tanks to a depth equal to the top of the reactor vessel - heat exchanger parting flange. A 20 ton traveling crane is located on rails in the building above the two tanks.

The refueling scheme adopted involves an underwater transfer of individual fuel elements by remote handling tools. The following assumptions were made:

1. A minimum of twelve feet of water will separate the operator from the uppermost active portion of any fuel element during the refueling transfer operation.
2. The thermoelectric heat exchanger and integral pressurizer must have a temporary storage space during refueling where repair work may be accomplished in parallel with refueling, if required.
3. The radiation level of the heat exchanger and pressurizer after extended periods of operation ordinarily will not preclude the accomplishment of repair work during refueling.
4. Spent fuel assemblies must decay in the storage tank for at least 120 days before removal to a permanent storage area or a reprocessing plant.

12.6.2 Detailed Refueling Procedure

Prior to starting the refueling procedure, it is assumed the plant has been shut down at least 8 hours. A summary of the refueling procedure follows:

1. Drain and remove tank shielding lids. Lower water level in tanks to top of reactor vessel. 0 hr. (assumed to be included in 8 hour period above).
2. Remove the heat exchanger - reactor vessel connecting stud nuts. Remove purification system lines and instrumentation connections. Cover all openings. 5 hr.

3. Refill water tanks to operating water level, using transfer pump. $3/4$ hr.
4. Lift heat exchanger - pressurizer assembly off reactor vessel and place in storage area. The core chimney will be removed as a part of the heat exchanger. 1 hr.
5. Refill water tanks to near the top. $3/4$ hr.
6. Remove the rods connecting the control rod drive mechanisms to the control rods. Remove core holddown hardware. $1/2$ hr.
7. Remove the fixed fuel assemblies, one by one, and place in the storage racks. 8 hr.
8. Unlatch fuel followers from the control rods and remove the control rods, one by one, and place in the storage racks. $1-2/3$ hr.
9. Remove fuel followers and place in the storage area. $1-1/3$ hr.
10. Following complete core removal, the reverse of the above procedure is followed to load in the new core. 17 hr.
11. Start plant per startup procedure. 9 hr.

The estimated time required to go from full power, through the refueling procedure and back to full power is approximately 53 hours.

13. SAFETY CONSIDERATIONS - CASE I

13.1 Safety Analysis

13.1.1 Introduction

This brief safety analysis discusses the various postulated accidents for the TCR-TE plant and some of the safeguards that are incorporated in the reactor to prevent damage to the core. Two classes of accidents are covered, as summarized below:

1. Reactivity Accidents

- a. Start-up accident
- b. Continuous rod withdrawal at power
- c. Cold and hot water accidents

2. Non-Nuclear Accidents

- a. Loss of coolant
- b. Loss of load
- c. Loss of coolant flow
- d. Chemical accident
- e. Missile accident

This report does not cover the hazards to the environment as a consequence of the so-called maximum credible accident involving partial core meltdown with partial release of fission products, because extensive analysis was made by others (Reference 13). These results should be applicable (within the scope of the current study) for the potential hazards to the environment posed by the TCR-TE reactor. The hazards summary studies which would be subsequently performed for TCR-TE would, of course, cover the consequences of the maximum credible accident and the related environmental hazards.

At full power the average coolant temperature leaving the reactor core is 552°F and the average coolant rise is 54°F. The water leaving the hottest channel has a quality of 5.7% because of boiling in the upper portion of the channel. Temperature changes coupled with the negative temperature coefficient act to limit smaller transients, while boiling in the hot channels operates to reduce and limit reactivity in larger transients where the power increases slowly.

Five control rods are provided for regulating the power level of the reactor, compensating for fission product buildup, counteracting the effects of fuel burn-up, and for scrambling the reactor either manually or automatically. Additional control to bring the reactor to cold shutdown is provided by the chemical shutdown system through which negative reactivity can be introduced.

13.1.2 Reactivity Accidents

13.1.2.1 Start-up Accident

The start-up accident is deemed unlikely because, in order for it to occur, there must be a series of multiple failures in the nuclear instrumentation and scram systems and at the same time there must be some errors or negligence on the part of the reactor operators. Ordinarily the reactor would be scrambled automatically on either a short reactor period or on a high neutron flux level. In addition, both flux level and reactor period are displayed on instruments located in the operating console and the operator can take corrective measures.

13.1.2.2 Continuous Rod Withdrawal at Power

Another type of reactivity accident is continuous rod withdrawal at power. In this case the reactor is assumed to be initially operating at or near full power, and a continuous withdrawal of control rods at design speed is assumed to occur. It is conceivable, though highly improbable, that such an accident could occur through a combination of equipment and personnel failures. If a continuous withdrawal of rods occurs, power level increases and reactor temperature rises slowly as a result of reactivity addition. Local boiling will increase and bulk boiling will occur in the reactor core thereby compensating for further reactivity addition after the temperature of the water exceeded saturation. Even if the high temperature scram fails to function, it is believed that the bulk boiling effect will limit the transient such that the operator still has ample time to shut down the reactor before any damage results. The scram circuitry, including that of manual scram, is independent of the circuitry which normally is used for manual control of the rods and, hence, is not affected by failures of the manual rod programming system.

The average flux for TCR-TE is 86,800 Btu/ft² and the peak flux in the hot channel is 300,000 Btu/hr ft². Moreover, the burnout flux based on the Bettis correlation is 1.24×10^6 Btu/hr ft², resulting in a DNB ratio of 4.6. This very large DNB ratio indicates the high degree of safety that is inherent in the TCR-TE core design.

13.1.2.3 Cold and Hot Water Accidents

The Case I unitized design contains an internal primary coolant circulation loop and only two sources of primary feedwater through which cold water could be introduced. The possibility of adding significant amounts of reactivity is small because the low flow rates of the make-up water are controlled by the charging and volume control pumps. The regenerative heat exchanger also serves to prevent the cold water accident. If cold water were to be introduced the addition of reactivity would be negligible because of the large primary system mass. Because of the negative moderator temperature coefficient, there is no danger of a power increase being caused by the introduction of hot water into the primary coolant system.

The addition of water volume, at any temperature, by the charging system would result in an increase in pressure, which would in turn result in a collapse of voids in the core and a temporary increase in power. The equilibrium rate of rise in pressure caused by the 4 gpm charging rate is estimated to be approximately 100 psi/minute, based on the present void volume calculation. This rate may be exceeded during the first minute of charging, due to the primary recirculation delay time. If the pressure transient were permitted to continue it would be terminated by operation of the pressurizer relief valve. However, the transient is slow enough that the operator should have sufficient time to take corrective action.

13.1.3 Non-Nuclear Accidents

13.1.3.1 Loss of Coolant Accidents

The loss of coolant resulting from a rupture of the primary coolant system represents the most serious type of accident for the TCR-TE. However, the probability of this occurrence for this accident is extremely low because of the compact design configuration, and because

of the exacting requirements imposed during design, manufacture and field erection. This accident, if it occurred, would result in a loss of the heat transfer capability of the reactor core and in subsequent damage to the core if sufficient cooling water is not supplied to keep the core covered. In any case involving loss of primary system pressure, automatic scram is effected by the control system, and charging pumps begin adding coolant at the rate of 4 gpm.

The largest break is postulated to be a ductile rupture of a 2 inch pressurizer spray line. The area of this ductile break is less than the corresponding pipe cross section. If a ductile rupture occurs, the charging pumps will probably not maintain system pressure, and the primary system will drop to nearly saturation pressure. A break of this size will expel water in three more or less distinct stages:

- a. Solid discharge of sub-cooled water
- b. Flash flow of steam, entraining some water
- c. Flow of steam only.

In the event of a loss of coolant accident the following conditions are expected to occur:

1. System pressure falls to saturation pressure and reactor scram is initiated. The energy produced during the power transient between full power level and decay heat level is expected to raise system pressure slightly. Solid discharge will last in the order of a second and will be followed by two-phase discharge that will prevail until the pressure vessel level falls below the point of the pipe break.
2. Once the point of the break has been uncovered, only steam will discharge through the break because the velocity of the rising steam above the water-steam interface in the vessel is too low to carry off water drops.
3. The scram time is expected to be about 1.5 sec., and during this time core power is being dissipated in the heat exchanger. The reactor core will not be damaged during this transient because it will be covered by water; recent investigations (Reference 14) have proven that it is safe to dissipate the decay heat by natural circulation in the core coolant.

The rate of steam generation by the internal energy of the primary coolant, as a function of time, is not known at the present time; consequently, it cannot be stated whether or not the core will be uncovered before the steam losses fall below the charging pump rate. It is expected that sufficient water and steam will remain in the vessel to prevent core meltdown following the accident, and two-phase blowdown. It is known, however, that the charging pumps can furnish more water than is lost by steam produced by core decay heat. A detailed study may prove the need for a greater than 4 gpm injection rate for a short period of time while the internal energy of the primary system is being dissipated.

Failure of a 3/8" diameter TE tube is less severe than a 1-1/2" pipe rupture.

13.1.3.2 Loss of Load Accident

With the use of a dissipative type of voltage regulator, a complete loss of electrical load would occur only during a programmed shutdown of the electrical system, in which case the reactor operator would be alert to reactor requirements; or through a double fault in the electrical system. In either case, no reactor control is necessary as this loss of electrical load is seen as only a loss of 17 to 26% of the thermal load by the reactor, and the reactor adjusts itself to the new conditions, through the void and temperature reactivity coefficients. A pressure rise of less than 150 psi occurs over a period of 3 to 4 minutes, and the steam relief valves in the pressurizer do not open.

13.1.3.3 Loss of Coolant Flow Accident

It is important that thermal damage to the reactor core be prevented under the most unlikely accident conditions, where this is practicable. One kind of accident which may result in thermal damage to a core in most types of reactors is that involving loss of coolant flow in the primary loop. This type of accident is not possible with the TCR-TE during startup or decay heat removal because a very low reactor power level will produce a relatively high coolant flow (See Section 4.3.5). Furthermore, because there are no primary pumps in the TCR-TE, a loss of coolant flow accident cannot occur during power operation.

A loss of secondary coolant flow would present a complete loss of thermal load to the primary system. This accident is very unlikely to occur because upon loss of power to any of the secondary pumps, the pump is shifted to battery power and then, in a short time, to diesel power. However, if the accident did occur, the low secondary flow scram would initiate a reactor shutdown. In the event of a partial loss of secondary coolant flow, reactor power would decrease slowly due to the action of the void and temperature reactivity coefficients while primary pressure would rise until corrective action could be taken by the operator or until a high pressure scram was activated.

Decay heat would be dissipated by boiling of primary coolant through the relief valves, the main coolant being replaced by the charging system.

13.1.3.4 Chemical Accident

Even in the event of core meltdown, no release of chemical energy by the reaction of water with the stainless steel cladding of the fuel is expected. While a reaction between components of stainless steel and water is thermodynamically possible, an energetic reaction is not to be expected on the basis of experience in industrial plants where molten stainless steel is mixed with water to produce a fine mesh powdered material.

No reaction of water with the TE element material is expected. This will be investigated in detail during the research and development program.

13.1.3.5 Missile Accident

The missile accident is usually considered in evaluating the safety of the vapor container. Even though no vapor container will be provided for this facility the following discussion is given from the viewpoint of personnel and equipment safety.

Although it is believed that no plausible missile could be released by the main coolant system, partial protection is provided for horizontal trajectories by the ground or earth surrounding the water shield tank. It is considered that the ductile austenitic materials of construction of the main coolant system piping will not

fail in a brittle manner when in contact with the hot compressed coolant. It is likewise considered that the plant reactor vessel, fabricated and tested according to the best techniques and under the proper codes will not fail and is not a feasible source for missiles.

13.2 Shielding - Case I

13.2.1 General

The Case I design consists of an integral reactor vessel - heat exchanger - pressurizer vessel immersed in a shield water tank which is adjacent to a fuel storage tank. This arrangement for the major equipment provides a relatively compact layout which minimizes radiation problems in comparison to the usual separation of these components. The radiation levels in normally occupied work areas will not exceed 2.5 mr/hr.

For shielding purposes, maximum use has been made of materials believed readily available at the plant site, such as earth, gravel and water, in order to reduce the weight of fabricated shield components which must be air transported.

13.2.2 Reactor Vessel and Refueling Modules

The reactor vessel - heat exchanger - pressurizer vessel is mounted in a neutron shield water tank having a 96-inch I.D. and a height of 28-1/2 feet. During normal plant operation, the tank is filled with water to a depth of approximately 16-1/2 feet, significantly reducing fast flux, thermal flux and gamma radiation originating in the reactor core. The depth is increased to 27-1/2 feet during the actual fuel transfer operation, giving a minimum of 12 feet of water between the fuel element and the operator during the transfer.

Shielding in the form of lead bricks is provided in the reactor vessel module on the ledge just below the reactor vessel - heat exchanger parting flange, to provide acceptable radiation levels during removal of the reactor vessel - heat exchanger studs. Normally, the parting occurs only during refueling at intervals in excess of two years. The lead shield is 8 inches thick and has an L-shaped cross-section, as shown in Figure 15. An additional 4-inch thick shadow shield is provided in the same area adjacent to the refueling tank.

The tops of the reactor vessel and refueling modules are provided with 20-inch deep dish-shaped covers, filled with water during normal operation.

13.2.3 Radioactive Auxiliaries Module

The radioactive auxiliaries module containing demineralizers and heat exchangers will be located underground adjacent to the refueling module. Approximately six feet of earth shielding is required.

13.2.4 Reactor Building

A detailed analysis of radiation levels in the reactor building above the reactor vessel and refueling modules has not been performed.

However, based on TCR work (Reference 3) the reactor building will have limited access during full power operation, except for a truncated cone-shaped area directly above the reactor module. Access to this cone-shaped area will not normally be permitted because of high radiation levels.

14. GENERAL PLANT DESCRIPTION - CASE II

14.1 Plant Description

The TCR-TE Case II plant is a 10 MW(th) air transportable direct conversion thermoelectric reactor system utilizing ambient air as the final heat sink. Minimum plant height has been stressed in establishing the design. Other "ground rules" for this case are described in the Introduction. The net plant electrical output is 271 KW. Figure 34 illustrates the general arrangement of the heat exchangers and the reactor-pressurizer vessel. The additional support modules are similar to those described for Case I.

As shown in Figure 34, the reactor vessel and the pressurizer are combined into one integral pressure vessel approximately 17 ft. high. Above the reactor vessel are four separate thermoelectric heat exchangers (primary to secondary), arranged radially about the pressurizer and connected to the reactor by Y-shaped main coolant pipes. Four final heat sink air blast coolers (secondary to tertiary), approximately 8'6" x 8'6" x 17' high, are located adjacent to the thermoelectric generators. The overall plant height is approximately 17-1/2 ft. Portable shielding, consisting of alternate layers of iron and water, is located around the reactor vessel core area.

The main pressure vessel consists of two sections bolted together - a main lower reactor vessel section containing the core and an upper section consisting of the pressurizer, heaters and the magnetically operated control rod drive mechanisms. Details of the plant, including the vessel, are covered in Section 16 of this report.

Each of the four thermoelectric generators contains 380 straight thermoelectric tubes of series-tubular swaged construction. The hot, high pressure main coolant water passes over the tube O.D. Jumper tubes are provided at the end of each thermoelectric tube for carrying the cooling water from the generator-heat exchanger to the headers. Single 6 in. O.D. pipes then carry this water to the air blast heat exchangers, which act as the final heat sink. Centrifugal pumps are provided in each of the four lines between the thermoelectric generators and the air blast heat exchangers, to give forced circulation. The four air blast heat exchangers are of finned U-tube construction, each having two 7 ft. diameter fans.

Adjacent to the air blast heat exchangers is the following supporting equipment: reactor auxiliaries, radioactive auxiliaries, shield water air-blast coolers, plant controls, inversion equipment, standby and startup power equipment, vital power control, maintenance, decontamination, sampling and waste disposal equipment. The supporting equipment is generally similar to Case I except for differences noted elsewhere in this report.

FIGURE 34

It is estimated that the complete Case II plant can be transported in seventeen C-130 aircraft plane loads, as noted on Table 18. As in Case I, the core fuel assemblies, fuel followers and control rods have been omitted from the initial plant weight summary, but included in the cost estimates. Since refueling has not been considered within the Case II scope, all refueling equipment has also been omitted from Table 18.

14.2 Plant Performance

The overall performance results for the TCR-TE Case II plant, as described in Section 14.1, are presented in the Summary of TCR-TE Plant Data, Table 2 of Section 2.

The thermoelectric generator output is 397 KWe from a 10 MW(th) core, resulting in a gross electrical efficiency of 3.97%. This gross electrical output is produced as 270 volt, 1470 amp dc power. The final net plant output, after inversion to 60 cps, 3 phase, 220 volt ac and the subtraction of reactor auxiliary power requirements and hotel load, is 271 KWe, giving a net plant electrical efficiency of 2.71%. The estimated auxiliary power requirements and inversion losses which form the basis for these efficiencies are summarized in Table 2 of Section 2 and discussed in greater detail in Section 23.

The Case II reactor primary system differs from the Case I system only in the heat exchanger region. The Case II design utilizes external straight-through tube heat exchangers, instead of the Case I U-tube integral design. The Case II primary loop unrecoverable pressure drops are 38.5 psf. The thermal driving head required to circulate 515,000 lb/hr of primary flow at Case II temperature and pressure conditions (same as Case I) is 11.5 ft.

An intermediate forced-circulation subcooled-water secondary loop with a total flow rate of 1,060,000 lb/hr has been selected as optimum. The closed system pressure varies from ambient to the maximum induced pumping head. The secondary coolant enters the primary-secondary heat exchangers at 195°F and exits at 227°F, still in the subcooled region. The maximum pumping power requirements (four pumps) for this coolant are 10 KWe.

The primary-secondary heat exchangers, which serve as the electrical generators in this case, contain "straight through" thermoelectric heat exchanger tubes identical in cross section to the Case I tube design, as shown in Figure 5 ($t_{TE} = 0.120"$ and $L_{CO} = 0.82"$). As in Case I, the hot reactor primary coolant circulates on the shell side of the tubes and the secondary coolant flows through the inside of the tubes. The total effective length of TE heat exchanger tubing required is 7600 ft, which is equivalent to 111,000 TE couples.

TABLE 18

TCR-TE PRELIMINARY PACKAGE LIST - CASE II

(Weights include skids and weatherproof covers, but do not include core fuel assemblies, fuel followers, control rods, and refueling transfer casks)

<u>Plane Load No.</u>	<u>Description</u>	<u>Est. Size</u>	<u>Est. Weight</u>
1	Reactor Vessel and Internals	6' x 6' x 12'	30,000 lb
2	Thermoelectric Heat Exchangers	7' x 7' x 7'	30,000 lb
3	Pressurizer and Main Coolant Piping	6'6" x 6'6" x 22'	28,300 lb
4	Air Heat Exchanger No. 1, Piping and Headers	8'6" x 8'6" x 27'	29,200 lb
5	Air Heat Exchanger No. 2, Aux. Module and Radioactive Aux. Module	8'6" x 8'6" x 30'	28,500 lb
6	Air Heat Exchanger No. 3 and Shelter	8'6" x 8'6" x 27'	29,000 lb
7	Air Heat Exchanger No. 4 and Waste Disposal	8'6" x 8'6" x 27'	27,000 lb
8	Shield Tank Section No. 1	5' x 5' x 6'	30,000 lb
9	Shield Tank Section No. 2	5' x 5' x 6'	30,000 lb
10	Shield Tank Section No. 3	5' x 5' x 6'	30,000 lb
11	Shield Tank Section No. 4	5' x 5' x 6'	30,000 lb
12	Shield Tank Section No. 5	5' x 5' x 6'	30,000 lb
13	Shield Tank Section No. 6	5' x 5' x 6'	30,000 lb
14	Crane	8'6" x 8'6" x 15'	27,000 lb
15	Plant Control and Inversion Equipment	8'6" x 8'6" x 30'	29,600 lb
16	Maintenance Equipment	8'6" x 8'6" x 30'	28,000 lb
17	Decontamination & Sampling	8'6" x 8'6" x 25'	18,100 lb
	Total Weight (including shipping containers but excluding core fuel assemblies, fuel followers, control rods, and refueling transfer casks)		484,700 lb

The thermoelectric material specified for the Case II design is "n" and "p" doped bismuth telluride. As discussed in Appendix I, its performance has been forecasted to January 1, 1963, when a Z_{ave} value of $2.20 \times 10^{-3} (^{\circ}\text{C})^{-1}$ is predicted. Using this material in the tube design shown in Figure 5, an optimum thermoelectric material conversion efficiency factor, ϵ_{TC} , of 18.0% results, as calculated in Appendix F.

Induced air at 80°F functions as the heat sink for the air blast coolers (secondary-tertiary heat exchangers). For an air flow rate of 84,000 scfm/unit and an air side pressure drop of 1.23 psf per unit, the maximum fan power required by all four units is 50 KW at 100% plant operation.

The Case II design has the inherent advantage of being operable where cooling water is scarce. The disadvantage of this Case II design lies in the reduced gross and net electrical outputs due to additional pumping requirements of the secondary and tertiary coolant, and to lower overall temperature differences across the thermoelectric tubes. Because of this second reason, Case I gross power outputs cannot be achieved in Case II.

15. REACTOR CORE - CASE II

The mechanical, nuclear and thermal-hydraulic designs and characteristics of the Case II reactor core are the same as those described for Case I in Section 4 of this report.

16. PRIMARY SYSTEM AND RELATED EQUIPMENT - CASE II

16.1 General

In the Case II plant arrangement the reactor and pressurizer vessels are combined into a single vessel assembly, while the thermoelectric tubes are contained within four separate heat exchangers. This arrangement is shown on Figure 35. The pressurizer furnishes the top closure for the reactor vessel and the two sections are attached by means of a bolted-flanged connection. The four TE heat exchangers are symmetrically positioned about the reactor-pressurizer assembly and are connected to the reactor vessel through a system of inlet and outlet piping.

The reactor vessel is provided with two inlet and two outlet nozzles. The piping branches from these nozzles are identical and symmetrical with respect to the vessel centerline. Each piping branch contains a "Y" fitting so that one reactor vessel nozzle services a connection to two adjacent heat exchangers. The "Y" branch lower pipe body is 12 inches O.D. and the two "Y" arms are 8 inches O.D.

As in the Case I concept, the primary coolant is circulated by means of thermal siphoning action. This requires that the heat sink (TE tubes) be located at an elevation above the heat source (nuclear core). To promote the required primary coolant flow rate in the Case II arrangement, it is necessary to locate the centerline of the TE heat exchangers 11-1/2 feet above the centerline of the core.

During operation, the primary coolant (which is heated during its passage through the nuclear core) rises inside the core support barrels to the two outlet nozzles. It then flows out these nozzles, through the adjacent piping to the "Y" fittings where it divides into two equal flows to the inlet nozzles of the heat exchangers. The primary coolant flows through the shell side of each heat exchanger, there giving up heat to the TE tubes which are cooled by secondary cooling water flowing through the tubes. The cold primary coolant then leaves the TE heat exchangers, flows down through the branch piping, through the "Y" fitting to the reactor vessel inlet nozzle. These nozzles discharge into the annular area formed between the core support barrels and the reactor vessel shell. The coolant is subsequently returned to the core inlet to repeat the cycle.

The heat transferred in the TE heat exchanger is dissipated to the atmosphere by means of air blast coolers and a closed intermediate cooling system. This secondary cooling system is unitized, with one air blast cooler servicing one TE heat exchanger. This arrangement allows one or more loops to be isolated from the system, providing suitable valves are included in the plant design. The plant reactor vessel - heat

PRIMARY SYSTEMS AND RELATED EQUIPMENT TCR-TE CASE II
FIGURE 35

exchanger arrangement is shown on Figure 34 . Figure 4 in Section 2 shows the flow paths for the primary and secondary cooling systems.

The primary system is designed to withstand a coolant pressure of 1500 psia at a temperature of 600°F. The secondary cooling system is of low pressure and low temperature construction. As with the Case I concept, all pressure carrying members are designed in accordance with the requirements of the "Structural Design Basis for Reactor Pressure Vessels and Associated Components" (Reference 7). It is also proposed that all ferritic pressure carrying members be fabricated of HY-80 material when a significant saving in weight can be effected.

In the Case II plant concept, integral shielding about the reactor vessel is supplied. This shielding is described in detail in Section 24.2

16.2 Reactor Vessel

Since the reactor vessel for the Case II concept is designed to contain the same nuclear core as the Case I vessel, the vessel assemblies are practically identical in both design and construction. Therefore, most of the discussions presented in Section 5.2 will apply here. In general, the two vessel arrangements differ in only two areas.

The major difference between the Case I and Case II reactor vessels is the addition of nozzles in the Case II vessel. Two inlet and outlet nozzles are installed at an elevation of approximately four feet above the centerline of the core. These nozzles have an inside diameter of approximately 12 inches and are equally spaced around the vessel. To facilitate shipment of the reactor vessel assembly, the nozzles are provided with flanged connections. This permits separate shipment of the adjacent piping branches.

Since the pressurizer vessel in the Case II arrangement is attached directly to the reactor vessel (instead of to the TE heat exchanger as in Case I) it was possible to reduce the diameter of the reactor vessel closure opening. This is considered desirable as it results in a saving in weight.

The reactor vessel weighs approximately 18,000 lbs, less attached piping, and has an overall length of about 10 feet.

16.3 Pressurizer

Except for the size of the steam bubble and the diameter of the closure opening, the pressurizer vessel arrangement for the Case II concept is identical to the Case I concept. Therefore, except as revised below, the discussion presented in Section 5.3 also applies here.

Since the contained primary coolant volume of the Case II plant is about 15% more than that of the Case I plant, it is necessary to increase the size of the steam bubble from 28 cubic feet to 32-1/2 cubic feet. This requires that the length of the cylindrical portion of the vessel be increased 4-3/4 inches. The overall length of the vessel is then increased to approximately 6 ft. 5 inches and the weight of the assembly, including heaters and control rod drive mechanisms, is 7,800 lbs.

16.4 Control Rod Drive Mechanisms

The design concept for the Case II control rod drive mechanisms is identical to that given for Case I. Consequently, all the information given in Section 5.4 also applies to Case II.

16.5 Thermoelectric Heat Exchanger Assembly

The Case II plant concept employs four (4) thermoelectric heat exchangers. These units are similar to conventional straight-through, horizontal, shell and tube heat exchangers except that there are no plenums at the ends of the vessels. Jumper tubes, identical to those in the Case I arrangement, are used to connect the individual TE tubes directly to the cooling water headers.

The heat exchanger shell is 66-1/2 inches in overall length and has an outside diameter of 30-1/2 inches. The wall is 3/4 in. thick, including 0.100 in. of stainless steel cladding. The tube plates are 3-1/4 inches thick, including 0.100 in. of clad on the inside and 0.25 in. on the outside. Both the tube plates and the shell courses are fabricated from HY-80 material.

There are 380 straight TE tubes, arranged on a 1-1/4 in. triangular pitch, in each heat exchanger. In order to reduce the possibility of leakage, these tubes are attached to the tube sheets by welding at each end of the tube. The individual tubes are connected together electrically by means of copper straps external to the heat exchanger. The provisions for attachment of the electrical straps and the jumper tube connectors are identical to those in the Case I concept. The advantages which the jumper tube arrangement offers in the Case I concept are also applicable for Case II.

Since the TE tubes are welded to both tube plates there is no provision for differential thermal expansion between the tubes and the vessel shell. Preliminary calculations based upon the most pessimistic conditions, have indicated that the stress in the TE tubes is somewhat high. Additional engineering effort will be required to investigate this problem in more detail. Should the stress condition in the tubes be prohibitive, a U-tube arrangement is possible. This latter arrangement has the disadvantage, however, of giving higher tube side pressure drops.

The shell side of each of the heat exchangers is furnished with flanged inlet and outlet nozzles. These nozzles are located so that the primary piping is connected to the vessels from beneath. Flow baffles are provided on the shell side of the units in order to obtain cross flow through the TE tube bundle, with a resulting improvement in the heat transfer performance.

Each heat exchanger is furnished with an inlet and an outlet cooling water header. Secondary coolant water is supplied to each inlet header by forced circulation. Coolant flows from the inlet header to the TE tubes through the inlet jumper tubes. After passage through the TE tubes the coolant flows through the outlet jumper tubes to the outlet header, and the heat is rejected in one of four air blast coolers. With the exception of the air blast coolers and the jumper tube assemblies, the secondary cooling system is fabricated entirely of carbon steel material.

The weight of each of the TE heat exchangers, less jumper tubes, primary piping and cooling water headers is 6300 lbs.

17. THERMAL AND HYDRAULIC DESIGN - CASE II

17.1 Introduction

There are two principal differences between the Case I and Case II thermal and hydraulic designs. Case I has the TE U-tubes inside the reactor vessel and uses a source of low temperature (80°F) water as a heat sink for the reactor heat. Case II has external thermoelectric heat exchangers in which the TE tubes are located. In addition, air-cooled heat exchangers form a tertiary system and heat sink for the secondary cooling water which transports the heat from the thermoelectric heat exchangers. Figure 4 is a schematic representation of these systems. The thermal and hydraulic design of the core is identical for Case I and Case II.

In Case II the primary coolant flows up through the core by natural circulation, and up through risers which branch out from the reactor vessel. At the top of the risers the coolant flows through the shell side of one of four horizontal standard heat exchangers. The cold primary fluid then flows back to the reactor through branched downcomers. The secondary loop consists of coolant which is heated as it flows through the TE tubes in the horizontal thermoelectric heat exchangers; it then flows through the finned tubes in one of the four air blast heat exchangers, where it is cooled. The secondary circuit utilizes forced circulation. Low velocity head propeller fans circulate across the finned tubes to improve cooling performance.

The Case II thermal and hydraulic performance results are presented in the Summary of TCR-TE Plant Data, Table 2 of Section 2. The equations and calculations used for this analysis are presented in Appendix E of this report.

17.2 Primary System

17.2.1 Core Thermal and Hydraulic Design

The core of the Case II reactor is identical to the one used in Case I. Temperatures, flow rates, flux, power, hot channel factors, flow distribution, etc. have the same magnitude as in Case I. (See Section 4.3)

17.2.2 Primary System Pressure Drop

The calculations and methods used for the Case I core and vessel pressure drops were also used for Case II since the conditions are identical. The local friction factors will have to be experimentally verified.

The heat exchanger shell side friction factor correlation of Donohue for turbulent flow across baffled tubular heat exchangers was used to calculate the shell side pressure drop. A triangular 1.25 in. tube spacing formed the basis for these calculations.

The Case II primary system total unrecoverable pressure drop was calculated to be 38.5 psf for the flow rate of 515,000 lb/hr. This includes a 10% margin which allows for unknowns and inaccuracies in the calculation of friction factors and form loss factors. This requires a thermal driving head (distance from center-line of core to center-line of heat exchangers) of 11.5 ft. A primary side film coefficient for the heat exchanger tubes of 1060 BTU/hr-ft²-°F was calculated using standard heat transfer correlations.

As a result of passing the primary coolant through the shell side of the thermoelectric heat exchangers, the pressure drop is substantially reduced, thereby reducing the overall plant height requirements. In addition, baffling of the shell side and passing the coolant across the TE tubes results in a fairly high heat transfer film coefficient.

17.3 Secondary System

17.3.1 General

The four thermoelectric heat exchangers form the heat source of the secondary system. The four air blast coolers form the heat sink. This system is shown schematically in Figure 4. The secondary system is a closed forced-circulation loop.

17.3.2 Comparison of a Boiling and a Non-Boiling Coolant

A study was made to determine whether a boiling or a non-boiling coolant gives better thermal and hydraulic performance for the secondary system. The performance was calculated for total secondary flow rates ranging from 66,100 lb/hr to 1,060,000 lb/hr. At these flow rates boiling begins approximately at the inlet and outlet, respectively, of the TE tubes. Figure 36 shows that the average temperature is lowest for the non-boiling case. This improves the thermoelectric generator performance since the thermal efficiency of the TE system is improved by making the average secondary coolant temperature as low as practical. Moreover, Figure 37 shows that the total secondary pumping power has a value of 9.9 KW for the non-boiling case at 1,060,000 lb/hr. It can also be seen from Figure 37 that the total TE tube length decreases as the flow rate increases.

TCR-TE PERFORMANCE - CASE II
 BULK TEMPERATURE OF SECONDARY COOLANT INSIDE TE TUBES

FIGURE 36

E. D. SK. 280439 B

TCR-TE PERFORMANCE - CASE II
 TOTAL LENGTH OF TE TUBE REQUIRED AND SECONDARY PUMPING POWER
 VS.
 SECONDARY COOLANT FLOW RATE

FIGURE 37

E. D. SK. 280457 B

Originally it was thought that a boiling secondary system would give higher heat transfer coefficients. Near atmospheric pressures this is only true for steam qualities below 0.5 where nucleate boiling occurs for the mass flow rates considered. Figure 38 shows that the thermal resistance is not constant along the axis of the TE tubes where boiling occurs in the secondary coolant. The thermal resistance for the non-boiling case (1,060,000 lb/hr) is constant and lower than the resistance for the other cases. The average secondary side heat transfer film for the non-boiling case in the thermoelectric heat exchangers is 3100 BTU/hr-ft²-°F, and the value in the air cooled heat exchangers is 735 BTU/hr-ft²-°F.

17.3.3 Pressure Drop and Heat Transfer

17.3.3.1 Two-Phase Pressure Drop

The Martinelli-Nelson two-phase frictional pressure drop correlation was used in the analysis. Over a wide range of conditions this correlation has been shown to hold within ± 30 to 35%. Recent investigation indicates that the two-phase pressure drop multiplier is also a function of mass flow rate. At a given pressure and steam quality, the two-phase pressure drop multiplier increases as the mass flow rate decreases. At pressures near atmospheric, the exact value of the multiplier has not been determined. No mass flow rate correction was used for the TCR-TE two-phase pressure drop analysis. If a correction had been made the two-phase pressure drops and loop pumping power would have been greater since the mass flow rates investigated are in the range of 1.0×10^6 lb/hr-ft². For flow rates below 1.0×10^6 lb/hr-ft² the corrected two-phase friction factors are higher than those the uncorrected Martinelli correlations would predict.

The secondary coolant enters the thermoelectric heat exchangers at 195°F and leaves at 227°F, for the selected reference design flow rate of 1,060,000 lb/hr. The total pumping power requirements for these flow conditions are 10 KWe.

17.3 3.2 Heat Transfer

Standard correlations were used for single phase heat transfer. For two-phase convective heat transfer the Dengler correlation was used. Both the Dengler heat transfer correlation and the Martinelli

TCR-TE PERFORMANCE - CASE II
THERMAL FILM RESISTANCE INSIDE TE TUBES

FIGURE 38

E. D. SK. 280456 B

pressure drop correlation use the correlating parameter X_{tt} . This correlating parameter is dimensionless and is a function of the quality, densities and viscosities of the liquid and steam phases. The Dengler correlation is applicable for bubble and slug patterns but does not correlate heat transfer data for annular flow.

17.4 Tertiary System - Air

The tertiary medium (air) is the final heat sink in the Case II TCR-TE system. Air entering the four air cooled heat exchangers at 80°F was assumed for these calculations. The pressure drop across the air side of the tubes is 1.23 psf, or 0.238 in. of water. For a flow rate of 84,000 scfm per unit, the air leaves the coolers at 178°F. The total fan power required for all four units is 50 KWe. Seven-foot diameter propeller type fans with a 50% efficiency was assumed. The air side heat transfer film coefficient was calculated to be 11.7 BTU/hr-ft²-°F. This was very influential in determining the overall tube heat transfer coefficient of 8.3 BTU/hr-ft²-°F. This value and the 77°F average log mean temperature difference across the finned tubes dictated the amount of tubing required.

The air cooled condensers designed by Westinghouse for the PM-1 reactor system have undergone extensive testing; thus, there is very good agreement between calculated and experimental results. In the design of the TCR-TE Case II air cooled heat exchangers every effort was made to use proven designs. For this reason, the air blast coolers were patterned after those designed for the PM-1 system.

There are four Case II air cooled heat exchangers. Each exchanger has 8 rows and 31 columns of 16 ft. active length U-tubes. The tubing was assumed to have the following characteristics: 17 BWG, 1 in. O.D., 3 in. pitch, 11 fins per inch, and 3.76 ft² heat transfer area per linear foot. This is the same tubing and number of fins per inch used for the PM-1 air cooled condensers. However, the tube spacing is increased in the TCR-TE, Case II, design to reduce fan power requirements. A U-tube design is utilized for greater flexibility and less mechanical complexity. The fin efficiency is greater than 90%.

The design heat load for the four heat exchanger units is 34×10^6 BTU/hr. The maximum heat capacity is 8.9×10^6 BTU/hr for each exchanger, or a total of 35.6×10^6 BTU/hr.

Because of the low net power output of the TCR-TE reactor, it is important that the power consumed by the auxiliary system be as low as practical in order to increase the overall plant efficiency. Considerable power conservation is achieved by using large diameter air fans to cool the secondary water. By reducing the fan speed the velocity head is reduced and the required brake horsepower is reduced. From basic fan laws, the discharge volume and the required brake horsepower vary as the square of the fan diameter and the speed varies inversely as the diameter of the fan.

There are two basic types of air cooled exchangers: a forced draft and an induced draft design. The forced draft type generally consumes less power than does the induced draft exchanger. However, the induced draft type generally gives better overall performance where vapor is being condensed. In the analysis of the secondary-tertiary system a non-boiling secondary loop has been found to give better overall thermal performance. Therefore, since the system selected is single phase, the use of a forced draft design may provide additional fan power conservation. The fan power requirements for the reference design were calculated using an induced draft design to be conservative.

To reduce the space required for the fan units single-bank fans are used. Moreover, a single-phase design simplifies the piping since non-condensable tubing and vents are not required. Another advantage of a single-phase design is that there is no problem of unequal condensation in different tubes, thus avoiding the resulting problems imposed by the use of orifices at the inlets of the tubes.

18. THERMOELECTRIC TUBES - CASE II

18.1 General

The general arrangement of the Case II thermoelectric heat exchangers (primary to secondary) is shown in Figures 4 and 35. The mechanical construction and overall performance are described in detail in Sections 16.5 and 19, respectively. The final performance results for the Case II reference design are presented in the Summary of Plant Data, Table 2 of Section 2.

The thermoelectric heat exchanger functions both as a mechanism for transferring heat from the primary coolant to the secondary medium, and as a generator of electricity. As the heat is transferred through the thick-walled heat exchanger tubes, a temperature gradient is produced across the thermoelectric material, thus generating electrical power.

Each of the four thermoelectric heat exchangers required contains 380 straight-through tubes, of 5 ft. active thermoelectric length, located on a 1.25 inch triangular spacing. This length of TE tubing will contain 111,000 TE couples. The tube cross-section design is identical to the Case I TE tube, as shown in Figures 5 and 39. The Case II tube design has no U-bends or bent portions as was required in the Case I design. Electricity is conducted external to the TE couples (through the tube sheet area and the heat exchanger external region) by annular copper tubing and end straps as described previously for the Case I design. The TE tube construction is discussed in detail in Section 7.2.1. The recommended fabrication techniques described for Case I in Section 7.2.2 are also applicable to the Case II tube design.

The individual TE couple length of 0.82 in. and the TE material thickness of 0.120 in. were adopted from Case I, since these values are also very nearly optimum for Case II conditions. The only differences in the entire mechanical construction of the TE tube assembly occur in the individual TE "n" and "p" leg axial lengths and the type of thermoelectric material. The "n" leg axial length is 0.448 in., while the "p" leg axial length is 0.362 in. The Case II design utilizes "n" and "p" doped bismuth telluride thermoelectric material, rather than lead telluride.

18.2 Thermal Characteristics of Thermoelectric Tubes

The thermoelectric tube thermal characteristics were calculated on the basis of results presented in Appendix E. The primary coolant, which flows on the shell side of the tubes, has an average bulk temperature of 526°F. For the selected secondary flow rate of 1.06×10^6 lb/hr, the average overall temperature gradient across the TE tubes is 315°F.

FIGURE 39

Figure 39 presents the average temperature profile across the Case II TE tube reference design cross-section. The primary or tube outside heat transfer film coefficient is $1060 \text{ BTU/hr-ft}^2\text{-}^\circ\text{F}$ and the secondary or inside film coefficient is $3100 \text{ BTU/hr-ft}^2\text{-}^\circ\text{F}$. Tube inside and outside fouling factors of $0.0002 \text{ hr-ft}^2\text{-}^\circ\text{F/BTU}$ were assumed. An overall TE tube heat transfer coefficient of $63.8 \text{ BTU/hr-ft}^2\text{-}^\circ\text{F}$ was calculated. The resulting heat flux in the TE portions of the tubes is $20,100 \text{ BTU/hr-ft}^2\text{-}^\circ\text{F}$. This requires a heat transfer area of 1690 ft^2 , or 7600 ft. of effective TE tubing.

Figure 39 predicts a temperature drop of 203°F across the TE material. This result reflects the effective TE material thermal conductivity correction factor which is derived in Appendix E and discussed in Section 7.3.

The comments on thermal stresses in Section 7.3 also are appropriate for the Case II tube design.

18.3 Thermoelectric Performance Calculations

Thermoelectric performance calculations for the TCR-TE, Case II, design are presented in detail in Appendix F. The results of these calculations are given in the Summary of TCR-TE Plant Data, Table 2 of Section 2. As discussed previously, these results are based on a TE couple length of 0.82 in. and a TE material thickness of 0.120 in. , which should be nearly optimum for Case II.

Based on the considerations given in Appendix I, bismuth telluride thermoelectric material with an average TE Material Figure of Merit of $2.2 \times 10^{-3} (^\circ\text{C})^{-1}$ was assumed in these calculations. Utilizing this TE material with the reference couple design, a thermoelectric material conversion factor, η_{TC} , of 18.0% is predicted. For the Case II temperature conditions, this material conversion efficiency gives a gross electrical conversion efficiency of 3.97% . The TE couple Design Figure of Merit is $2.05 \times 10^{-3} (^\circ\text{C})^{-1}$. The couple internal electrical resistance is $176.8 \times 10^{-6} \text{ ohms}$, and the current flow is 122 amps . The optimum external to internal load ratio, M is 1.39 . A total of $111,000$ couples are required to produce 397 KW of gross electrical power for the Case II TCR-TE plant.

The final net efficiency predicted for the Case II plant design is 2.71% , which is equivalent to an electrical output of 271 KW from a plant with a 10 MW(th) reactor core.

As in Case I, the aforementioned results are based on the assumption of negligible electrical and thermal resistance at the conductor-TE material interfaces. It is believed that this can be achieved by utilizing the series-tubular geometry fabricated by swaging and sintering techniques.

19. THERMOELECTRIC GENERATOR ANALYSIS - CASE II

19.1 General

The general arrangement of the thermoelectric heat exchanger-generator is shown in Figures 4 and 35. The mechanical construction of the heat exchanger-generator assembly and the related components are described in detail in Section 16.5. This assembly is located as one of four external straight-through heat exchangers above the reactor vessel. It consists of 380 tubes per heat exchanger, or a total of 1520 tubes each of 5 ft. effective TE length. The tubes are connected in series and parallel by end straps, as described in Section 8.1 for Case I. The four external generators are connected in parallel so that any one can be shut-down for maintenance purposes, etc. without disrupting the performance of any other unit.

Figure 5 illustrates the arrangement of the thermoelectric couples in a typical tube assembly and shows the resultant "axial-radial stepped" current flow path which is induced. The end portions of the Case II tubes and the connections between them are identical to the Case I tubes except that no curved or bent portions are required in the Case II straight-through arrangement.

19.2 Performance Results

The results of the thermoelectric generator performance analysis are presented in the Summary of TCR-TE Plant Data, Table 2 in Section 2. The equations and sample calculations are presented in Appendix F. As discussed in Appendix I, bismuth telluride material properties forecasted to January 1, 1963 were used as the basis for this study.

The gross electrical power produced by the TCR-TE Case II generator from a 10 MW(th) reactor core is 397 KW in the form of 270 volts, 1470 amps dc power. Thus, a 3.97% plant gross efficiency is attained. With the estimated auxiliary power requirements and inversion losses as discussed in Section 23, a plant net electrical power output of 271 KW is calculated; this is equivalent to a 2.71% overall plant net efficiency.

For the Case II heat exchanger - generator design a total effective thermoelectric tube length of 7600 ft. is required to produce the required electrical output and to exchange sufficient heat. This tubing is installed as 1520 tubes, each containing 5 ft. of effective thermoelectric length. Each of the four heat exchanger-generator units would contain 380 tubes or three parallel electrical paths, since the total generator requires twelve parallel paths to produce 270 volts, 1470 amps dc power. This network provides a sufficiently high voltage output, and still affords a very high degree of reliability.

The results presented above for the performance of the TCR-TE, Case II, plant are based on conditions and assumptions chosen or specified for the reference design. To a certain extent, improvements in these conditions and in design concepts can and should be realized, resulting in related improvements in the plant net efficiency. Some of the possible methods of improving the TCR-TE design in order to achieve higher efficiencies are considered Appendix G.

A general discussion on thermoelectric generator-reactor system control considerations is included in Appendix D. General thermoelectric generator characteristics are discussed in that Appendix, and curves indicating performance capabilities are given. The discussion also includes the effect of load changes on the generator, and how these relate to reactor operation.

20. ELECTRICAL INVERSION SYSTEM - CASE II

The comments on the Case I inversion system (Section 9) are considered applicable to Case II, because the Case II thermoelectric generator current flow of 1470 amps (@270 V dc) is essentially equal to the Case I flow of 1638 amps (@ 250 V dc).

Since Case II does not have a lake water supply for the resistor bank tank, a separate source of water must be provided, as noted in Section 21, or natural circulation air cooling could be used.

21. AUXILIARY SYSTEMS - CASE II

The auxiliary systems for Case II are similar to those described in Section 10 for Case I, with certain additions and deletions. This section will cover the changes only, with equipment which is similar in both cases not being described again.

The major differences are:

1. The secondary, lake water, open coolant system for Case I is replaced by a closed secondary forced circulation coolant system. The final heat sink for Case II is ambient air circulated by means of air blast coolers, while Case I has no tertiary coolant. This change deletes, for normal operation, approximately 25 KW for the lake water pumps and adds 10 KW for the closed loop forced circulation pumps and 50 KW for the air blast fans.
2. The Case I water makeup system sources for the plant have been deleted because Case II has no open lake water loop or shield water purification loop. Water suitable for plant use, including input to the resistor bank tank, must be supplied from external means available at the site.
3. The shield water and refueling tanks provided in Case I have been eliminated through the use of integral shielding for Case II and the assumption that refueling will be accomplished by temporary means (not defined for this study). However, the water used in the integral shield tank also requires cooling. This cooling is accomplished by the shield water cooling loop as in Case I. The shield water coolers also serve as the cold side of the decay heat exchanger, the non-regenerative heat exchanger and the waste disposal heat exchanger. The shield water purification loop is eliminated since spent fuel storage facilities are not specified, within the scope of the Case II study.
4. The requirement for the large water storage tank, used in Case I primarily for storage and supply of water during refueling water level changes, will depend upon the refueling scheme ultimately adopted.

Tables 19, 20 and 21 which follow, summarize the Case II auxiliary systems pumps, heat exchangers, and tanks and demineralizers, respectively.

TABLE 19

TCR-TE AUXILIARY SYSTEM PUMPS - CASE II

<u>Function</u>	<u>No. Req'd.</u>	<u>Type</u>	<u>Rated Flow (gpm ea.)</u>	<u>Normal Head (psi)</u>	<u>Design Pressure (psig)</u>	<u>Design Temp. (°F)</u>	<u>Motor H.P. (ea.)</u>	<u>Approx. Input (KW)(ea.)</u>
Charging	2	Same as Case I (See Table 12 , Section 10)						
Makeup,Transfer	1	Same as Case I (See Table 12 , Section 10)						
Decay Heat	1	Same as Case I (See Table 12 , Section 10)						
Component Cooling	2	Same as Case I (See Table 12 , Section 10)						
Water Storage Transfer	1	Not required, if refueling by temporary means.						
Chemical Transfer	1	Same as Case I (See Table 12 , Section 10)						
Closed Sec. Loop	4	Cent.	530	6	10	250	3.4	2.5

TABLE 20

TCR-TE AUXILIARY SYSTEM HEAT EXCHANGERS - CASE II

<u>Function</u>	<u>No. Req'd</u>	<u>Heat Loads (Btu/hr)</u>		<u>Design Flow</u>		<u>Design Press. (psig)</u>		<u>Design Temp. (°F)</u>	
		<u>Normal</u>	<u>Design</u>	<u>Tubes</u>	<u>Shell</u>	<u>Tubes</u>	<u>Shell</u>	<u>Tubes</u>	<u>Shell</u>
Regenerative	1	Same as Case I (See Table 13 , Section 10)							
Non-Regenerative	1	Same as Case I (See Table 13 , Section 10)							
Decay Heat	1	Same as Case I (See Table 13 , Section 10)							
Shield Core	1	Same as Case I (See Table 13 , Section 10)							
Air Cooled Condenser (Pure water makeup)	1	Same as Case I (See Table 13 , Section 10)							
Shield Water Air Coolers	4	Same as Case I (See Table 13 , Section 10)							
Final Heat Sink Air Blast Coolers	4	3.4x10 ⁶ total	3.56x10 ⁶ total	1.06x10 ⁶ lb/hr total	33.6x10 ⁴ cfm total	35	Ambient	250°	200°

TABLE 21

TCR-TE AUXILIARY SYSTEM TANKS AND DEMINERALIZERS - CASE II

<u>Function</u>	<u>No. Req'd</u>	<u>Size (ft³)</u>	<u>Design Pressure (psig)</u>	<u>Design Temp.</u>	<u>Dimensions</u>	<u>Installed Position</u>
Low Press.	1	Same as Case I (See Table 14 , Section 10)				
Pure Water Storage	1	Same as Case I (See Table 14 , Section 10)				
H ₂ Flask	1	Same as Case I (See Table 14 , Section 10)				
Chemical Control	1	Same as Case I (See Table 14 , Section 10)				
Boric Acid	1	Same as Case I (See Table 14 , Section 10)				
Water Storage	1	Not required, if refueling by temporary means.				
Expansion	1	Same as Case I (See Table 14 , Section 10)				
Resistor Bank	1	Same as Case I (See Table 14 , Section 10)				
Weir	1	Same as Case I (See Table 14 , Section 10)				
Purification Demineralizer	1	Same as Case I (See Table 14 , Section 10)				

22. NUCLEAR INSTRUMENTATION - CASE II

22.1 Nuclear Instruments

The nuclear instrumentation is the same as for Case I, and is discussed in Section 11 of this report. The detectors will be located outside the reactor vessel, in the water between the shield plates shown in Figure 35.

22.2 Radiation Monitoring

The radiation monitoring instrumentation is the same as for Case I, and is discussed in Section 11.5. However, since the secondary system is a closed system, any long half life activity resulting from a tube leak will build-up in the secondary side. Therefore, after a period of time small leaks will be detectable by the radiation monitoring equipment.

23. PLANT OPERATION - CASE II

23.1 General

The plant operation for Case II is similar to the Case I operation procedures described earlier. This section will cover only items of operation which are significantly different from those described for Case I in Section 12. Refueling for Case II has not been considered except to the extent that it was assumed to be accomplished by temporary means.

23.2 Cold Startup

The cold startup procedure is the same as in Case I except that the minimum auxiliary diesel power is estimated at 55 KW rather than 40 KW, owing primarily to the added power requirements for the tertiary cooling fans. As in Case I, alternate startup procedures are possible wherein a shorter starting time is traded for larger installed diesel generator capacity or vice versa. The total time from zero to full power utilizing the starting procedure outlined for Case I, is approximately 9 hours for Case II.

Table 22 shows an estimated breakdown of the maximum auxiliary cold startup requirements. The totals of the power requirements are not shown because the maximum load will be considerably less than the sum, since the loads will be sequenced.

23.3 Normal Operation

Normal plant operation is similar to that for Case I. Table 23 shows the estimated normal operation auxiliary power requirements, based on average values. From the table, it can be seen that an auxiliary power load of 126 KW is expected during normal operation, of which 18.2 KW are for reactor auxiliaries, 99.7 KW are for the secondary and tertiary systems, and 7.8 KW are for the hotel load. These power requirements are supplied by the thermoelectric generator and inversion equipment.

23.4 Transient Operation

The transient operating characteristics of the TCR-TE Case II plant are expected to be similar to those of Case I. Enlargement of the primary system volume by 15% over the Case I design results in a slightly more sluggish response, while the pressurizer steam volume has been increased proportionally in order to maintain the system stability margin.

Again, use of a dissipative type converter precludes any load change from reaching the reactor under normal conditions. In the event of failure of this feature of the electrical system, the reactor would feel a loss of approximately 33% of the thermal load, in response to a 100% loss of electrical load. This is somewhat greater than the corresponding 26% thermal load loss felt in Case I. Thus a greater temperature and volume surge in the primary system would result. The pressure surge resulting from a loss of the electrical load is not expected to be great enough to open the pressurizer safety valves.

23.5 Shutdown

Plant shutdown for Case II is similar to plant shutdown for Case I, described in Section 12.5. As in Case I, the shutdown power requirements are less than the startup loads and, therefore, will not affect the auxiliary diesel power requirements.

23.6 Refueling

The contract wording for this study, specifying the use of integral shielding with modified radiation requirements based on an exclusion area, has resulted in the six segmented iron-water shield tanks noted in Section 24.2. The use of shielding and refueling tanks similar to those specified for Case I was discarded because they do not appear to fulfill contract requirements although they are considered a more desirable approach. The end result, however, has been to add several plane loads of portable shielding, compared to Case I, and to eliminate the simple refueling and fuel storage scheme of Case I. With the shield water and refueling tanks eliminated, it will be necessary to utilize temporary equipment for refueling. This equipment and a refueling scheme have not been investigated. However, a temporary tank and hoist arrangement similar to that proposed for the ML-1 plant, Reference 15, appears feasible. Further work in this area is required at the start of a subsequent design and engineering program, since the refueling scheme adopted can have a major effect on the general plant arrangement.

With a portable tank and hoist arrangement, the refueling time will be longer than that noted for Case I since a longer plant shutdown time prior to the start of refueling will be required. Also, the temporary placement and removal of tanks and general adjacent equipment, and the bolting and unbolting operations using remote handling tools will consume considerable time in addition to the actual fuel transfer operation. A temporary pressurizer storage area, with appropriate hoist equipment, must also be provided.

TABLE 22

TCR-TE MAXIMUM STARTUP LOAD - CASE II

(Individual Values Are Not Additive)

<u>REACTOR SYSTEMS</u>	<u>MAX. KW</u>
Vital Power Bus	3.0
Control Rods	1.0
Pressurizer Heaters	46.0
Charging Pumps	4.0
Component Cooling Pumps	4.0
Sump Pumps	1.0
Makeup & Chemical Pumps	2.0
Shield Water Cooling Fans	8.0
 <u>SECONDARY AND TERTIARY SYSTEM</u>	
Secondary Loop Pumps	10.0
Tertiary Cooling Fans	50.0
 <u>BUILDINGS AND FACILITIES</u>	
Air Compressor	1.0
Lighting	2.5
Power Outlets	0.7
Heating and Ventilation Fans	4.5

TABLE 23
TCR-TE CASE II
AUXILIARY POWER LOAD
DURING NORMAL OPERATION

<u>REACTOR SYSTEMS</u>	<u>AVERAGE KW</u>
Vital Power Bus	2.0
Control Rods	1.0
Pressurizer Heaters	3.8
Charging Pumps	1.0
Component Cooling Pump	2.0
Sump Pumps	0.2
Makeup and Chemical Pumps	0.2
Shield Water Cooling Fans	8.0
Sub-Total	18.2
<u>SECONDARY SYSTEM</u>	
TE Closed Cooling Loop Pumps	10.0
Inversion Power Losses	39.7
Sub-Total	49.7
<u>TERTIARY SYSTEM</u>	
Air Blast Fans	50.0
Sub-Total	50.0
<u>BUILDINGS AND FACILITIES</u>	
Air Compressor	0.1
Lighting and Battery Charger	2.5
Power Outlets	0.7
Heating and Ventilation Fans	4.5
Sub-Total	7.8
Total	126 KW

24. SAFETY CONSIDERATIONS - CASE II

24.1 Safety Analysis

24.1.1 Introduction

In most areas, the safety analysis for Case I (Section 13.1) also applies to Case II. Therefore Case II will be discussed briefly to point out only the additional considerations for Case II.

24.1.2 Reactivity Accidents

The analysis of all the reactivity accidents for Case I also applies to Case II. For the rod withdrawal accidents this is based on the fact that all the nuclear and thermal hydraulic parameters of the core are the same for both cases. The Case II design has separate primary loops but, in the reference design, there are no valves to isolate a loop. Therefore, there is no occasion for one loop to become colder than the others to create the possibility of a cold water accident. If a decision is made to provide such valves in the Case II plant, then additional studies on the possibility of a cold water accident will be carried out.

24.1.3 Non-Nuclear Accidents

24.1.3.1 Loss of Coolant Accident

The loss of coolant accident for Case II could be more serious than for Case I because a break in the 12-inch loop piping must be considered. For a break of this magnitude safety injection is required to keep the core covered while the internal energy of the primary coolant system is being dissipated. In the engineering phase for Case II, a detailed study will be made to determine the maximum leakage rate and the amount of safety injection water required.

24.1.3.2 Loss of Coolant Flow

The considerations for loss of primary and secondary flow are the same as for Case I.

A loss of air to the secondary system coolers would present nearly a complete loss of thermal load to the secondary system and thereby to the primary system. As in the case of loss of secondary coolant flow, reactor

power would slowly decrease and primary system pressure would rise until a high pressure scram was initiated. Probably the secondary system relief valves would operate as the temperature and pressure of the secondary system would rise.

24.1.3.3 Chemical and Missile Accidents

The considerations for these accidents are the same as for Case I, and are described in Sections 13.1.3.4 and 13.1.3.5.

24.2 Shielding - Case II

24.2.1 General

Radiation shielding is designed to provide biological protection wherever a potential health hazard exists. The radiation sources consist of the reactor and main coolant system, and certain of the auxiliary systems.

The shielding requirements for a nuclear powered plant are normally divided into the following categories:

1. Primary shielding, which must attenuate the gamma and neutron radiation emanating from the core and reactor vessel to design levels during normal operation and after shutdown of the reactor.
2. Secondary shielding, to supplement the primary shield during normal operation and, in addition, to attenuate the radiation emanating from the primary coolant.
3. Fuel handling shielding, to provide adequate protection for operators during removal or transfer of fuel.
4. Auxiliary shielding, to attenuate the radiation from that equipment which processes primary coolant.

The Case II shielding requirements differ from Case I in that an exclusion area around the reactor vessel is permissible. The Case II shielding is designed so that radiation intensities at ground levels 500 ft. from the center line of the reactor vessel will not exceed 5 mr/hr during normal operation.

24.2.2 Primary Shield

The reactor core is surrounded, radially, by a water reflector, a stainless steel core support barrel, a stainless steel thermal shield, and a steel reactor vessel. In total there are, between the core boundaries and the outer diameter of the reactor vessel, at least 5 inches of steel and 5.5 inches of water.

The primary shield consists of a tank segmented into six equal sections, each weighing approximately 14 tons dry, and containing alternate layers of iron and water as shown in Figure 40. When assembled, the shield will be in the form of an annular tank, surrounding the lower portion of the reactor module, with a thickness of 35 inches and a height of 68 inches. The total weight of the complete shield is approximately 90 tons.

Between the first and second iron shielding plates is an annular water-filled space which will be used for the nuclear instrumentation. The clearance required for the nuclear instrumentation is approximately 6 inches.

During normal full power operation, the fluxes at the outer surface of the tank are:

1. Neutron Flux	2.0×10^6 n/cm ² -sec
2. Gamma Flux (2.5 Mev)	1.0×10^5 γ/cm ² -sec
3. Gamma Flux (7.5 Mev)	5.0×10^4 γ/cm ² -sec

Immediately after shutdown, the radiation fluxes at the outer surface of the primary shield will be less than 10 mr/hr.

24.2.3 Secondary Shield

Because of the exclusion radius provided, 500 feet from the center line of the reactor, a material secondary shield is not required. The exclusion radius provided serves to reduce the radiation from the primary equipment to the allowable total level of 5 mr/hr.

24.2.4 Fuel Handling Shield

The refueling procedure for the Case II plant is considered to be beyond the scope of this study. Therefore, a refueling concept has not been determined and shielding requirements for this purpose have not been specified. However, during the engineering phase of a subsequent contract, suitable refueling shielding requirements would be established and the designs would be specified.

TCR-YE-CASE 11
SEGMENTED SHIELDING TANK

SECTION A-A
FIGURE 40

E.D. SX. 288268 C

24.2.5 Auxiliary Shielding

There are normally two auxiliary systems which will process primary coolant; these are, the primary coolant purification system and the shutdown cooling (decay heat removal) system. During normal operation these systems will be adequately shielded by the exclusion distances provided. After shutdown, the radiation levels from these systems, except for the demineralizer, will be reduced by continued operation of the purification system. Consequently, shielding of these systems for access after shutdown will not be required.

The primary loop demineralizer will require approximately 6 feet of earth shielding in order to permit safe access to the auxiliary equipment during plant shutdown.

NOMENCLATURE

A	heat transfer area or electrical flow area
A_f	fluid flow area
b	projected perimeter
C_p	specific heat, constant pressure
D	diameter
D_e	equivalent hydraulic diameter
D_{eg}	equivalent diameter for heat transfer
e_{ct}	carnot efficiency of thermocouple
e_g	overall thermoelectric couple efficiency or generator gross efficiency ($e_g = e_{ct} \times e_{TC}$)
e_{net}	overall system net efficiency
e_{TC}	thermocouple material efficiency conversion factor = $\frac{e_g}{e_{ct}}$
F_q	peak to average heat flux
F_θ	peak to average film drop
$F_{\Delta H}$	peak to average enthalpy rise
F_r	tube bank heat transfer multiplier for cross flow
f	friction factor
G	fluid mass velocity = $\frac{W}{A}$
G_s	cross flow mass velocity based upon minimum flow area
G_w	mass velocity through the heat exchanger baffle window
g_c	mass-force conversion factor, $\frac{\text{lbs mass-ft}}{\text{lbs force-sec}^2}$
g	acceleration of gravity
H	enthalpy, or pressure head

H_T	thermal driving head height
h	tube heat transfer film coefficient, or height
I	load current
I_{co}	couple current
K	thermal conductance
K_{co}	couple thermal conductance
K_h	hydraulic loss coefficient
k	mean material specific thermal conductivity; also, nuclear multiplication factor
L	length
$\bar{L}$	total tube length containing TE material in heat exchangers; also, flow length
L_{co}	total length of TE couple ($= L_p + L_n + 2 L_i$)
L_i	thickness of insulation in TE couple between "n" and "p" legs
L_n	length of TE thermoelement "n" leg
L_p	length of TE thermoelement "p" leg
L_1	length of reactor core exhibiting sub-cooled flow
L_{2-p}	length of reactor core exhibiting two-phase flow
ℓ_e	length of electrical flow path
M	TE generator external to internal load ratio
N	total number of TE couples in generator
N_b	number of banks of tubes for cross flow
N_{PR}	Prandtl number $= \frac{C_{u,p}}{k}$
N_{Re}	Reynolds number $= \frac{\rho V De}{\mu} = \frac{G De}{\mu}$
N_s	total number of TE couples in series
N_p	total number of parallel paths in TE generator

P	power
p	system pressure
Q	heat flow rate
Q_j	Joule heat generated per couple
Q_{Pe}	amount of energy due to Peltier effect
Q_{Pe-c}	Peltier effect at TE cold junction
Q_{Pe-h}	Peltier effect at TE hot junction
Q_q	heat flux transferred from hot to cold junction of thermoelement by conduction
Q_R	total primary reactor heat entering thermoelements
Q_S	total heat rejected from thermoelements
Q_{Th}	Thomson heat generated in each thermoelement
$Q_{(th)}$	thermal heat generated
r	radius
R_{co}	internal couple resistance
R_g	modified Martinelli void fraction
R_L	external generator resistive load
r_e	equivalent hydraulic radius
r_f	tube fouling factor
R	specific electrical resistance or thermal resistance
s	tube pitch or spacing
S	specific gravity
T	temperature
$\bar{T}$	average temperature across TE material

t	material thickness, fin thickness
TDH	thermal driving head pressure
U_o	overall heat transfer coefficient, TE heat exchanger tube
V	load voltage
V_s	flow velocity
V_v	magnitude of vector sum of component velocities
v	specific volume
W	flow rate; also, power per couple
w	width
w/co	watts per couple
x	quality of coolant
Z_D	TE couple <u>design</u> figure of merit
Z_M	TE couple <u>material</u> figure of merit
α	Seebeck coefficient
β	ratio of "p" to "n" thermoelement lengths = $\frac{L_p}{L_n}$
ΔH_q	enthalpy change
$\Delta k/k$	reactivity
Δp	pressure drop
ΔT	temperature gradient or change
ΔT_o	TE tube overall temperature difference
ϵ	heat exchanger effectiveness
η	fin efficiency parameter
θ	angle
μ	micro or one millionth; also, viscosity

ρ	density, or electrical resistivity
σ	area ratio
ϕ^2	Martinelli - Nelson two-phase multiplier
Ω	ohms, or fin efficiency

SUPERSCRIPTS

(None)	primary coolant
'	secondary coolant, if water
''	air as the coolant
T	Total
E	Engineering
N	Nuclear

SUBSCRIPTS

ave.	average condition
b	bulk
c	cold side
co	thermoelectric couple
core	nuclear reactor core
F	fan
f	saturated liquid, or frictional
G	generator
g	saturated vapor
h	hot side
i	internal or inlet
i.cond.	TE assembly inside electrical conductor (See Fig. 5)

i.in.	TE assembly inside insulation (See Fig. 5)
i.t.	TE assembly inside pressure tube (See Fig. 5)
LMTD	log mean temperature difference
m	mean
n	TE "n" type material or element
o	external, or exit, or overall
o.cond.	TE assembly outside electrical conductor (See Fig. 5)
o.in.	outer insulation of TE assembly (See Fig. 5)
o.t.	outer tube of TE assembly (See Fig. 5)
p	TE "p" type material or element
2-p	two phase
T	total
TE	thermoelectric
t	TE tube assembly
3	thermoelement hot conductor
4	thermoelement cold conductor

LIST OF REFERENCES

<u>Reference Number</u>	<u>Description</u>
1	NYO-2937, "Study of Remote Military Power Applications, Report No. 1, Summary", January 1960, Kaiser Engineers
2	ORNL-2985, "The Feasibility of an Unattended Nuclear Power Plant", September 1960, ORNL
3	WCAP-1590, "Thermal Circulation Reactor Design Study", June 1960, Westinghouse APD
4	WAPD-AD-TH-556, "A Method of Predicting Steady State Boiling Vapor Fractions in Reactor Coolant Channels", G. W. Maurer, 1959, Bettis Atomic Power Laboratory
5	ASME-60-HT-36, "Natural Circulation Tests with Water at 800 to 2000 psia under Non-Boiling, Local Boiling and Bulk Boiling Conditions", O. J. Mendler, A. S. Rathbun, N. E. Van Huff and A. Weiss
6	WAPD-R-(TH)-583, "Generalized DNB Equations for Flow of Water in Rectangular Channels at 800 to 2000 psia", B. W. LeTourneau, 1960, Bettis Atomic Power Laboratory
7	PB-15187, "Tentative Structural Design Basis for Reactor Pressure Vessels and Directly Associated Components", U. S. Dept. of Commerce, Office of Technical Services
8	YAEC-155, "Design and Test Analysis of the Magnetic Jacking Positive Latch Control Rod Drive Mechanism", L. J. Balog, A. A. Bishop and T. F. Widmer, July 1959, Westinghouse APD
9	WAPD-217, "The Calculation of Pressure Drop and Flow Distribution Within a Reactor Vessel in a Pressurized Water Nuclear Water Reactor System", J. S. Busch, L. L. Lynn and C. F. Bonilla, August 1959, Bettis Atomic Power Laboratory
10	WCAP-1659, "Thermoelectric Nuclear Fuel Element Quarterly Progress Report - October-December 1960", J. C. Danko, January 10, 1961, Westinghouse APD

Reference
Number

Description

- 11 WCAP-1811, "TE Heat Exchanger Demonstration Unit - Final Report", J. C. Danko, Westinghouse APD (Scheduled for publication in July 1961)
- 12 "Semiconductor Thermoelements and Thermoelectric Cooling", A. F. Ioffe, Infosearch Ltd., London, Copyrighted 1957
- 13 MND-M-1853, "PM-1 Nuclear Power Plant Hazards Summary Evaluation", October 15, 1959, Martin Nuclear Division
- 14 WAPD-AD-TH-559(1959), "Summary of Emergency Cooling Tests on Electrically Heated Subassemblies with Water at 2000 psia", Bettis Atomic Power Laboratory
- 15 IDO-28550, "The ML-1 Design Report", May 16, 1960, Aerojet General Nucleonics
- 16 WCAP-1810, "Recommended Research and Development Program for Thermoelectric Power Conversion", J. C. Danko, Westinghouse APD (Scheduled for publication in July 1961)
- 17 WASH-743, "AEC Reference Fuel Processing Plant", October 1957, AEC Division of Civilian Application, Washington D.C.
- 18 "Thermoelectricity Quarterly Progress Report No. 3", August 13, 1959, Westinghouse Research Laboratory
- 19 Unpublished Design Study for a 830 KW(e) Gross Thermoelectric Plant Using Reactor Coolant as the Heater for the Thermoelectric Generator, by R. A. Markley, 1960, Westinghouse APD
- 20 "Thermodynamic Properties of Compressed Water", by T. C. Tsu and D. T. Beecher, 1957, ASME
- 21 WCAP-1737, "Preliminary Core Design of a 500 KW(e) Thermoelectric Reactor", J. C. Danko, Westinghouse APD, March 1961
- 22 WAPD-TH-410, "Heating, Local Boiling and Two-Phase Pressure Drop for Vertical Upflow of Water at Pressures Below 1850 psia; Test Data and Correlations", B. W. LeTourneau and M. Troy, October 1958, Bettis Atomic Power Laboratory

Reference
Number

Description

- 23 WAPD-TH-326, "Revised Pressure Drop Recommendations for Pressurized Water Reactor Design". B. W. LeTourneau and N. C. Scher, May 8, 1957, Bettis Atomic Power Laboratory
- 24 WAPD-TH-219, "Review of Martinelli-Nelson Pressure Drop Correlation", N. C. Scher, July 1956, Bettis Atomic Power Laboratory
- 25 A.I Ch.E. Journal, Volume 5, No 4, pages 427-432, by H. S. Isbin, H. A. Rodriguez, H. C. Larson and B. D. Pattie (1959)
- 26 WAPD-AD-TH-470, "Natural Circulation of Water at 1200 psia Under Heated Local Boiling and Bulk Boiling Conditions - Test Data and Analysis", A. S. Rathbun, N. E. Van Huff and A. Weiss, December 1958, Bettis Atomic Power Laboratory
- 27 "Thermoelectric Properties of Lead Telluride Alloy Systems", Minnesota Mining and Manufacturing Co., Electrical Products Lab., St. Paul 6, Minnesota, Revision June 6, 1960
- 29 WCAP-1745, "Thermoelectric Nuclear Fuel Element Quarterly Progress Report, January-March 1961", J. C. Danko, April 10, 1961, Westinghouse APD