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MASTER

ADVANCED COAL-FUELED COMBUSTOR/HEAT EXCHANGER TECHNOLOGY STUDY

Contract EF-77-C-01-2612

RESEARCH & DEVELOPMENT PLAN

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1.0 INTRODUCTION

This report is submitted in partial fulfillment of the requirements of Contract EF-77-C-01-2612, "Advanced Coal Fueled Combustor/Heat Exchanger Technology Study". The contracted effort constitutes the first phase of what is expected to be a three-phase program to advance coal fueled combustor/heat exchanger technology to be utilized in conjunction with high temperature, closed cycle gas turbine/Rankine power conversion systems. The ultimate objective in evaluating such CCGT systems is to permit more efficient conversion of U.S. coal resources to electrical energy. The objective of the three-phase study and development program is to advance the technology of coal fired CCGT/Rankine power conversion systems to a state of technology readiness, i.e., to a point where no major risks remain for full-scale commercial development.

Much of the rationale for studying the coal fired closed cycle gas turbine power generation system lies in two factors. The closed cycle gas turbine power system, which utilizes a non-condensing working fluid, is capable of higher overall thermal efficiencies than is the conventional steam based Rankine system utilized in present day steam power stations. It utilizes higher working fluid temperatures to achieve this higher efficiency. Additionally, the utilization of the closed cycle as opposed to the "open" gas turbine cycle, isolates the turbomachinery from the products of coal combustion. These coal combustion products are so dirty, corrosive, and erosive that no practical system for their direct utilization in gas turbines has yet been devised, and near term achievement of practical coal fired open cycle gas turbines appears unlikely. The direct coal firing of heat exchangers, by comparison, is present day state-of-the-art at the lower working fluid temperatures typical of today's steam based power cycles. The operating requirements for the coal fired combustor/heat exchanger of a closed cycle gas turbine power conversion system differ from those of steam boilers in several respects, particularly as regards maximum heating surface temperatures. But they are sufficiently similar that the attainment of technology readiness for such combustor/heat exchangers is expected to be attainable for modest development costs and in the near future, thus permitting more efficient utilization of the only economically abundant U.S. fuel, coal.

The effort contracted under EF-77-C-01-2612 consisted entirely of studies, analyses, design effort and reporting. No fabrication or test effort was involved. The technical goals for the contracted study effort were:

A. Provide four preliminary designs of coal fueled combustor/heat exchangers suitable for use with high temperature closed cycle gas turbine/Rankine power conversion systems. Two of the four preliminary designs were to be designed for a nominal maximum working fluid temperature of 1550 F and utilize the direct combustion of coal along with metallic heat exchanger surfaces. Two of the preliminary designs were to utilize a nominal working fluid temperature of 1750 F or higher, and additionally could utilize coal derived fuel and/or nonmetallic heat exchanger surfaces. The nominal unit rated capacity was to be 350 MWe.

B. An analysis of the "key features" of the four preliminary designs created in A above was to be conducted and documented, to determine those key features which are areas of uncertainty in the design and critical to the success of the design.

C. A detailed plan was to be prepared to spell out the analysis work, design refinement work, and development test work necessary on the identified problem areas, or areas of design uncertainty, in the combustor/heat exchanger designs (as identified in the key features analysis). This program plan for future work was to be sufficiently detailed to form a basis for planning the next phase of the overall effort necessary to achieve "technology readiness", which is attained when there are no major technology risks in full size commercial development.

This report on "Identification of Required Research Effort" is supplied in response to Task 6 of the EF-77-C-01-2612 contract Statement of Work. The objective of this task was to "prepare a detailed plan to eliminate through (1) further analysis work, (2) design refinement work, and (3) test work, those identified problem areas, or areas of design uncertainty in the combustor/heat exchanger design as identified in the Key Features Analysis". This report presents a research and development plan for each of the four preliminary designs which were synthesized under this contract. Each plan is intended to cover the effort needed from now to the attainment of a condition of "technology readiness". Technology readiness was defined in the RFP as a condition existing when:

1. All major problems associated with the performance specification goals have been solved and the solutions successfully demonstrated.

2. Documentation has been prepared throughout the technology development program such that all assumptions and conclusions can be transferred from the technology developer to the technology user.

3. The availability of knowledge is such that several equipment manufacturers could be expected to build equipment in a specific time period on a firm fixed price basis in a competitive manner.

The judgment that a state of technology readiness has been achieved appears likely to be a subjective one, and depend upon the design concepts being readied as well as upon the experience and point of view of the observers. In a general way, the concept of technology readiness employed in this study assumes that it will have been demonstrated when analyses and testing of components of the combustor/heat exchanger embodying specifically identified problem areas has been successfully conducted, and when a significantly sized pilot installation or module of the heat exchanger embodying substantially all of the concept in question has been designed, fabricated and successfully operated for several thousand hours.

The research efforts indicated for the entire period from now to the achievement of technology readiness have been addressed in this report. That effort has been broken down into two phases, an initial period designated as Phase II, (the study documented herein is Phase I), in which additional analyses, design refinement, materials and component testing, and perhaps small module testing would take place in preparation for the embodiment of the preliminary design concepts in an "all up" module or pilot plant installation. Following Phase II, a Phase III program would include the design, erection and operation, for at least several thousand hours, of a pilot plant embodiment of the concept. The size of the pilot installation would be significant with respect to the technical features of the concept.

The contents of this report include:

a. A section defining the philosophy and methodology utilized in devising the R&D program, and its relationship to the other aspects of the contract study.

b. A detailed R&D plan for each of the four preliminary designs of coal fired CCGT combustor/heat exchangers synthesized during the course of this contract.

c. A conclusion and discussion of results section concerning the significance of the R&D plans.

Three technical summary reports have already been issued to document other results of this study:

a. PCS 78-06 the "Closed Cycle Gas Turbine, Coal Fired Heat Exchanger Design" report covers all of the fired heat exchanger design effort and describes the combustor/heat exchanger design criteria which were applied to the designs, the conceptual combustor/heat exchanger designs from which selections were made for preliminary design effort, and the four preliminary designs which were created.

b. PCS 78-07 the "Working Fluids and Cycle Analysis Report" documents the effort that was conducted to define appropriate performance requirements for the fired heat exchangers.

c. PCS 78-08 the "Key Features Analysis Report" provides an analysis of key features of each of the four preliminary combustor/heat exchanger designs.

The final report, RI/RD78-212, summarizes the results of the entire study and includes material on CCGT "balance of plant" equipment, i.e., unfired heat exchangers, turbomachinery, piping, etc., which is not covered in the technical reports. Additionally, the results of "cost of electricity" evaluations are presented.

2.0 R&D PLANNING PHILOSOPHY AND METHODOLOGY

The purpose of this section of the R&D Plan report is to outline the philosophy and methodology utilized in devising the R&D plans presented.

The fundamental purpose of the R&D plans presented herein is to advance the technology of coal fired combustor/heat exchangers for supply of the heat input to closed cycle gas turbine systems to a state of "technology readiness". Technology readiness is defined as the condition existing when:

1. All major problems associated with the performance specification goals have been solved and the solutions successfully demonstrated.
2. Documentation has been prepared throughout the technology development program such that all assumptions and conclusions can be transferred from the technology developer to the technology user.
3. The availability of knowledge is such that several equipment manufacturers could be expected to build the equipment in a specific time period on a firm fixed price basis in a competitive manner.

R&D programs to achieve technology readiness may be structured in many different ways, depending on philosophy and funding. The "man on the moon" program, for instance, was an outstanding example of what can be achieved with unlimited funding and concurrent development of major full scale hardware items. By contrast the development of new technology under conditions existing in the commercial market place may sometimes be slow indeed.

The philosophy underlying the R&D plans presented herein assumes that relatively modest funding will be available in the early stages of each development program, as CCGT combustor/heat exchanger development will be competing for funds with many other advanced energy concepts. Demonstrated progress on confirmation of the major technical and economic features of the designs in the early stages of the program will then permit the addition of more extensive funding, and attainment of technology readiness.

A second major question affecting the R&D planning is "what constitutes proof that all major problems have been solved and solutions demonstrated". The philosophy generally adopted here is that the 350 MWe CCGT combustor/heat exchangers are sufficiently different from existing equipment that it will be necessary to achieve several thousand hours of successful operation of a significantly large and complete embodiment of the design concepts.

In line with the philosophy discussed above, the programs defined herein to achieve a state of technology readiness generally provide that analysis and design refinement and testing will first be conducted that will develop the crucial components of the combustor/heat exchanger concept, then demonstrations of a significantly complete model or other embodiment of the concept will be conducted and finally several thousand hours of demonstrative operating time on that embodiment will be attained. Obviously there can be many variations on these plans, and considerable overlap, depending on the design and on events.

R&D plans are presented for each of the four preliminary designs that were synthesized during this study. Each of the designs is responsive to different operating conditions as defined by a different CCGT cycle. The studies conducted in the area of cycle and working fluid definition, as well as the rationale for selecting the particular working fluids and cycles for which preliminary designs were prepared, are summarized in report PCS 78-07, the "Working Fluids and Cycle Analysis" report. The four preliminary designs are described in report PCS 78-06, the "Closed Cycle Gas Turbine, Coal Fired Heat Exchanger Design" report. The key features of the four preliminary designs are described in report PCS 78-08, the "Key Features Analysis Report".

In the process of creating these R&D plans, the drawings, analyses and key features of each of the preliminary designs were separately examined, appropriate R&D activities to attain technology readiness in each key feature area were planned, the timing of the R&D activity analyzed, and costs estimated.

An overall R&D plan for each of the four preliminary designs has been projected for the entire time period estimated to be required to achieve the condition of technology readiness. In the planning and conduct of technology advancement programs of this nature, it is typical that the visibility for planning is much better for the near-term period than it is for the entire development period. Also typically the activities in the later portions of the development period are dependent upon events and data and technology developed in the earlier period. Indeed, the justification and funding of the later phases of development may well be dependent upon results of the early phase. For all of these reasons, the plans are presented first for the entire development period, outlining the entire strategy. Then more detailed plans are presented in each case for a "Phase II" stage, which would follow immediately after the Phase I study program being reported herein, and consist largely of laboratory and component testing, analyses and design refinement, planning for pilot installation R&D, facilities acquisition, and the like. This phase is readily visible and presented in some detail. Its successful completion would justify a Phase III, the program completion.

The R&D plans presented herein are entirely concerned with the combustor/heat exchanger and its auxiliary equipment. No attention is given to the R&D which may be required for pressure piping exterior to the combustor/heat exchanger, unfired heat exchangers, turbomachinery, etc. It is assumed that development and availability of such equipment will be to a schedule that supports combustor/heat exchanger R&D.

3.0 DETAILED R&D PLANS

This section presents a separate, detailed research and development program for each of the four preliminary designs created on this contract. An overall R&D plan for each preliminary design is first outlined, covering the entire period from the close of this study to the attainment of "technology readiness". The initial R&D period, constituting Phase II of each overall program, is then detailed.

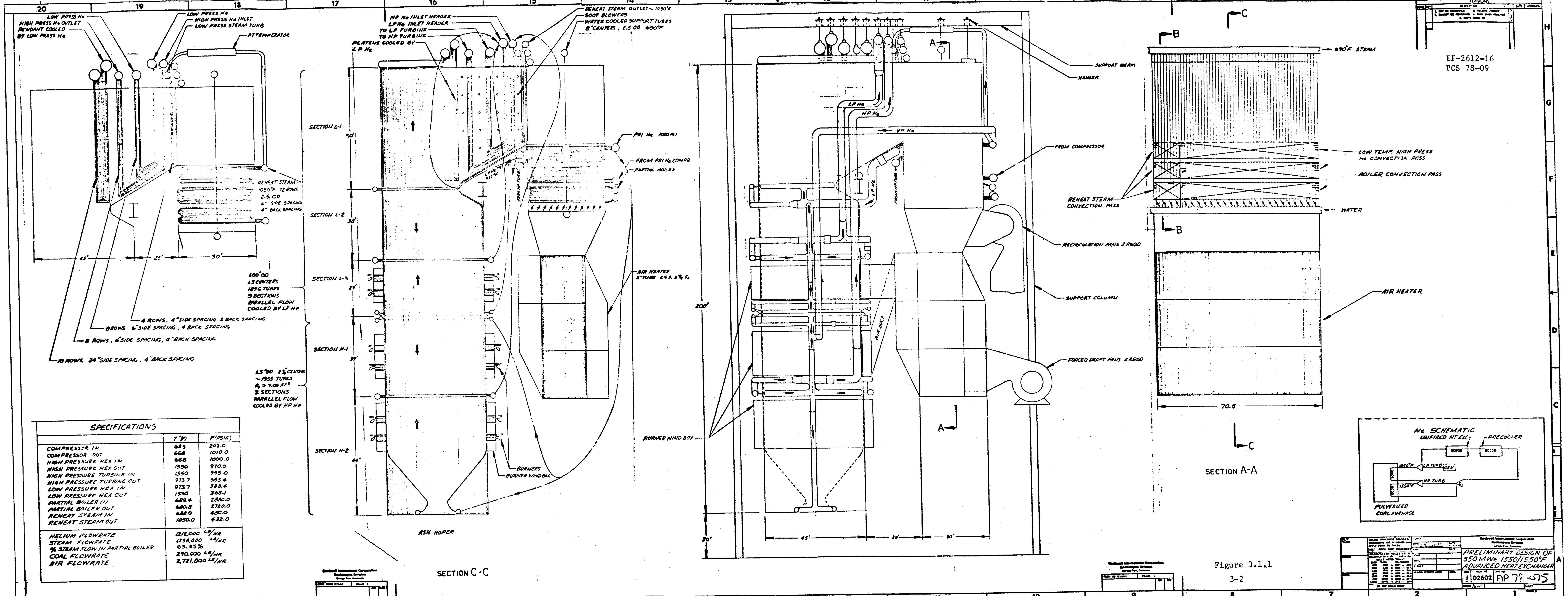
For the convenience of the reader, the preliminary design drawing, and an artist's rendition of each of the preliminary designs is included in this report. The drawings are discussed in detail in PCS 78-06 the "Closed Cycle Gas Turbine, Coal Fired Heat Exchanger Design" report. Additionally presented here are the tables of design features that have been evaluated as "key features" requiring R&D for the resolution of technology questions. These tables are discussed in detail in PCS 78-08, the "Key Features Analysis Report".

3.1 R&D PLAN - 1550 F CCGT WORKING FLUID TEMPERATURE, DRY-BOTTOM PULVERIZED COAL-FIRED COMBUSTOR/HEAT EXCHANGER

The reference design conditions selected for preliminary design synthesis are presented in Table 3.1.1, a drawing of the preliminary design is presented in Fig. 3.1.1 and an artist's rendition of the design is presented in Fig. 3.1.2. The key features of this preliminary design as analyzed under the key features task of the contract are summarized in Table 3.1.2.

The R&D requirements indicated by the technology conditions disclosed by the key features analysis are summarized in Table 3.1.3 along with a projected overall chronology.

EF-2612-16
PCS 78-09



SPECIFICATIONS

	T °F	P (PSIA)
COMPRESSOR IN	683	202.0
COMPRESSOR OUT	668	1010.0
HIGH PRESSURE HEX IN	668	1000.0
HIGH PRESSURE HEX OUT	1550	970.0
HIGH PRESSURE TURBINE IN	1550	955.0
HIGH PRESSURE TURBINE OUT	973.7	383.4
LOW PRESSURE HEX IN	973.7	383.4
LOW PRESSURE HEX OUT	1550	368.1
PARTIAL BOILER IN	689.4	2880.0
PARTIAL BOILER OUT	680.8	2720.0
REHEAT STEAM IN	638.0	480.0
REHEAT STEAM OUT	1050.0	432.0
HELIUM FLOWRATE	1212,000 LB/HR	
STEAM FLOWRATE	1258,000 LB/HR	
% STEAM FLOW IN PARTIAL BOILER	63.35%	
COAL FLOWRATE	290,000 LB/HR	
AIR FLOWRATE	2,721,000 LB/HR	

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Canoga Park, California

PRELIMINARY DESIGN OF
350 MWe 1550/1550°F
ADVANCED HEAT EXCHANGER

J 02602 AP 78-575

Figure 3.1.1

350 MWe PULVERIZED COAL FIRED HELIUM HEATER

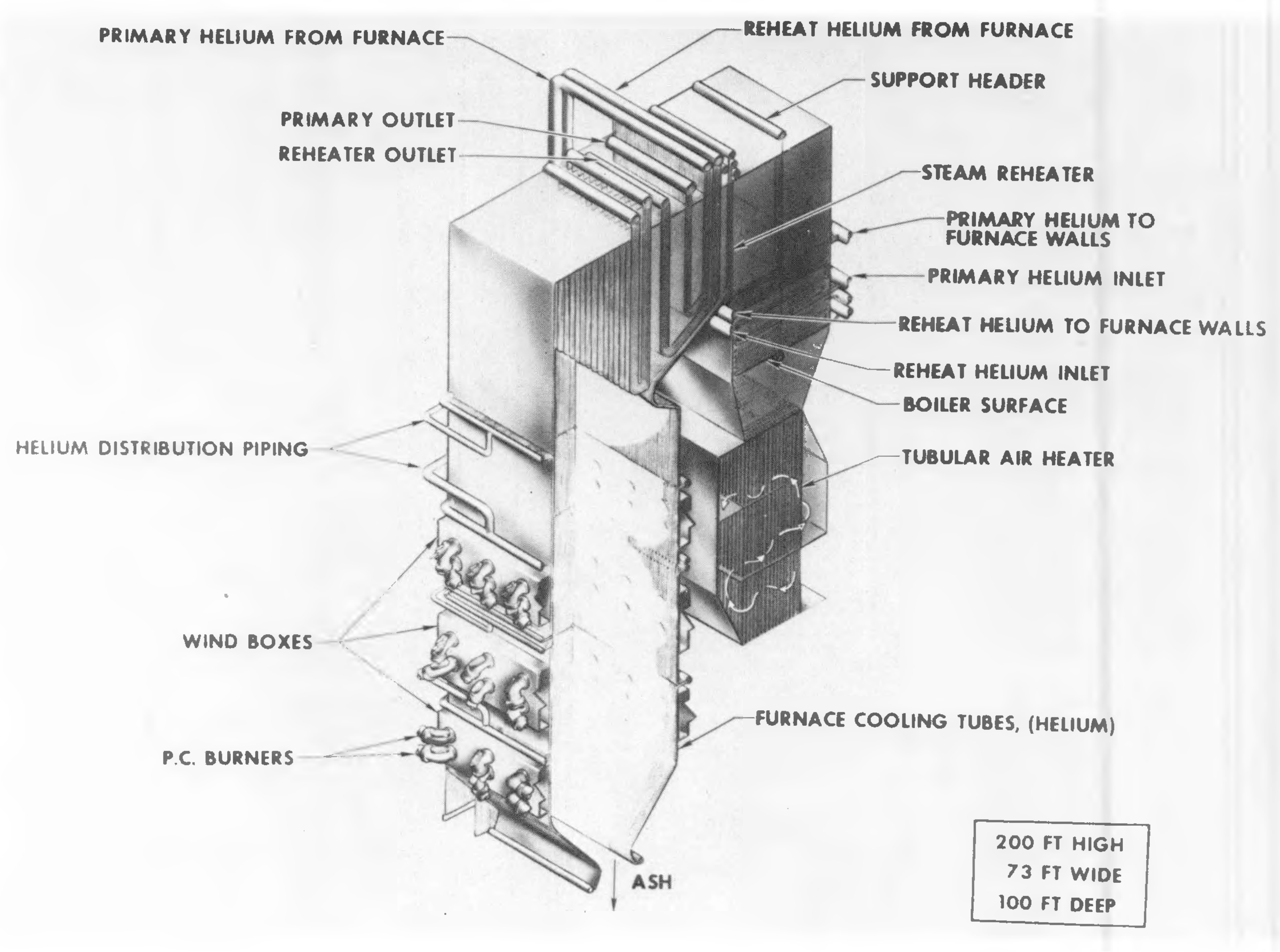

Figure 3.1.2

Table 3.1.1 NON-RECUPERATED CCGT CYCLE/STEAM BOTTOMING CYCLE

He 2 -Stage Exp.(1550 F/1550 F/Adiab.)1-Stage Comp.(80 F)
Comp. Ratio (5) Exp. Ratio (4.55) PR Factor (91%)
Steam Reheat (2400 P/1050 F/1050 F) Condensing (80 F)

Heater - gas in	644.06F	1368.62H	1000P	HP turbine PR=2.459
gas out	1550.00	2491.98	970	967 P_{in} 393.25 P_{out}
Reheater - gas in	985.93	1792.54	391.6	LP turbine PR=1.85
gas out	1550.00	2491.98	380.6	379.0 P_{in} 204.9 P_{out}
Non-Fired				Comp. PR = 5
Boiler - gas in	1144.69	1989.40	204.4	200.5 P_{in} 1002.5
gas out	790.00	1549.58	203.4	P_{out}
water/steam in	682.19	1102.70	2640.	
steam out	1054.16	1494.00	2480.	
Fired				
Boiler - water in	687.06	781.98	2840.	
water/steam out	685.55	1102.70	2680.	
Economizer - gas in	790.00	1549.58	203.4	
gas out	135.00	737.39	2020.	
water in	83.17	59.39	3040	
water out	688.53	781.98	2880.	
Cooler - gas in	135.00	737.39	202.0	
gas out	80.00	669.19	201.0	
cooling water in	65.00			
cooling water out	110.00			
Fired Reheater - steam in	638.00	1322.50		
steam out	1050.00	1549.66		

Heat Balance Based on 1 lb CCGT Gas Flow

Heat Input	Heater	1123.36	
	Reheater	699.44	
	Fired Steam Boiler	360.49	
	Fired Steam Reheater	255.33	2438.62
Energy Output	Non-Fired Boiler	439.82	
	Non-Fired Economizer	812.19	
	Cooler	68.20	
	CCGT Gen. Output	494.04	502.58
	CCGT Mech. & Gen. Loss	8.54	

Steam Cycle Heat Input	1867.83
Net Thermal Eff.	.3954
Generator Output	738.54
Lb Steam/lb Gas Flow	1.124
Overall Cycle Efficiency	.5054
Lb Gas Flow/Hr (376.34 MW)	1041819.
Lb Steam Flow/Hr	1171005.
Gas Cycle Output MW	150.84
Steam Cycle Output MW	225.50

TABLE 3.1.2 KEY FEATURES ANALYSIS (1550 F Working Fluid Coal-Fired Dry Bottom PC Combuster/ Heat Exchanger Preliminary Design)

Requirement	Feature	Evaluation			Notes
		Technology Available*	Marginally Available**	Needs R&D***	
1. Fabricability	Containment	x			
	Convection Surface	x			
2. Operability	Combustor/HEX System:				
	Burners	x			
	Furnaces		x		
	Convection Surface	x			
	Emissions	x			
3. Safety	Pressure part code compliance			x	For metals operating at over 1500 F
	Fireside explosions, fires, etc.	x			
	Turbine trip (loss of coolant)	x			
4. Durability	Metals operating at under 1100 F	x			
	Metals operating at over 1100 F			x	Corrosion, low-cycle fatigue
	Refractories, casing, insulation, etc.	x			
5. Maintainability		x			
6. First Cost	Size and surface		x		
	Superalloys		x		
7. Operating Costs	Fuel	x			
	Other Consumables	x			
	Manpower	x			
	Maintenance		x		

* - Generally acceptable solutions at hand.

** - Some doubt or dissatisfaction

*** - Positive needs identified

TABLE 3.1.3. OVERALL R&D PLAN - 1550 F DRY BOTTOM PC COMBUSTOR/HEX

MAJOR REQUIRED RESEARCH	Study			Test			YEARS														
	Analysis	Design Refinement	Detail Design	Lab	Boiler	Pilot	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
							← PHASE II	—	→	← PHASE III	—	—	—	—	→						
							← Laboratory & Component Testing, Analysis, Design Refinement	—	→	Pilot Design, Fabrication & Erection	—	→	← Pilot Operation	—	→						
Materials of Construction																					
Metals at > 1100 F - furnace walls				x	x	x	← Lab & Existing Boiler	—	—	—	—	→	←	—	→						
- convection surface				x	x	x	← Lab & Existing Boiler	—	—	—	—	→	←	—	→						
- Code acceptance	x						←	—	—	—	→										
Internally insulated piping -																					
- Technical feasibility	x			x		x	←	→					←	—	→						
- Code acceptance	x								←	—	→										
PC Furnace Operations																					
Furnace absorption rate control by flue gas recirculation	x				x	x	←	→					←→								
Analysis & Design Refinement																					
Working fluid composition, temperature, & pressure optimization							←→														
Functional design optimization							←	→													
Prepare "setting drawings"	x	x	x					←	→												
Operational Proof of Complete Combustor/HEX Embodiment										←	—	—	—	—	→						

3.1.1 Overall Plan and Chronology

The overall plan an chronology of Table 3.1.3 indicates a nine year R&D program extending from the present to the achievement of "technology readiness". The timing and nature of the program are strongly influenced by several factors:

1. The nature of the high temperature metals development program, which involves fire side corrosion, working fluid side corrosion, and long term creep and stress rupture effects, is such that a relatively long test period is required to obtain significant results.

2. Another factor tending to require a long program is that a relatively large dry bottom pulverized coal furnace installation is required in order to obtain significant overall results from a "pilot" installation. Smaller, laboratory scale, pilots may provide misleading information and for that reason might not be accepted as having demonstrated technology readiness. The relatively large pilot installation will need several years for design, fabrication and erection.

3. A fortunate and offsetting condition with respect to timing and R&D expense is that much significant testing for materials research and pulverized coal dry bottom furnace operations can be obtained by using existing dry bottom pulverized coal steam boiler furnaces as test beds. This can be done with little or no interference to their normal function of providing steam for the production of electricity.

The above factors underlie the rationale of the R&D program plan presented in Table 3.1.3. The program structure contains a three year "Phase II" period during which laboratory and steam boiler contained testing is conducted, along with analyses, design refinement, optimization of operating conditions, and detailed design problem soliving. Sufficient design detail and experimental evidence would be sought during this Phase II period to permit the adequate design of a pilot installation and to justify the funding of Phase III. During Phase III the major effort would be the design, fabrication, erection and operation of a significantly sized pilot plant installation. It would be operated for a sufficient period to justify confidence that technology readiness had been achieved. Additional effort during Phase III would include the continuation of appropriate laboratory and component research to supply any missing inforamtion, to support pilot operations, and to secure acceptance of the required safety code modificaitons.

The size of the pilot installation necessary to obtain credible results during Phase III is believed to be on the order of 10% of a full scale 350 MWe unit, i.e., on the order of 25 to 50 MWe. The first 25 MWe complete CCGT heater installation might cost in the neighborhood of 12 million 1978 dollars. Such a unit is unlikely to be economically viable for continued operation by an operating utility over a thirty year life. It may be necessary to simply write off the costs of that installation as necessary to the development of the CCGT concept. An alternative is to install the pilot installation for a cogeneration application, for which the pilot size would be within the range of economic viability for long term operation.

Metal materials research with respect to fire side corrosion resistance at exterior metal temperatures of 1050 to 1600 F is basic to the program. Much research in the lower portion of this temperatures range has been conducted over the last thirty years in the search for materials to permit higher superheat temperatures in steam boilers. The R&D plan for CCGT applications would be coordinated with previous and on-going research for high temperature steam boiler applications. It is not expected that any new alloys will be invented to provide the required properties. Available candidate alloys will be evaluated with respect to their capability for coping with the environment naturally present in dry bottom pulverized coal combustors. Additionally, continued research will be conducted to determine whether the environment itself can be modified by additives or operating practice to provide acceptable fire side corrosion conditions. It is expected that laboratory evaluations, sample evaluations in existing steam boilers, and pilot installation research will be appropriate. The Phase II effort will provide the foundation for specifications of alloys in the Phase III pilot plant. Continuing laboratory and steam boiler evaluations are planned during the Phase III operation as well.

While fire side corrosion considerations will occupy the major portion of the metals development program, concurrent R&D will be conducted to confirm adequate corrosion resistance on the working fluid side of the metals, to complete the definition of the long term strength characteristics of candidate alloys, (i.e., creep and stress rupture), and to pursue the acceptance of the candidate alloys by the Boiler and Pressure Vessel code.

Internally insulated piping for the high temperature CCGT working fluids is not essential to the design of the 1550 F dry bottom PC combustor/heat exchanger. However, there is a great deal of intermediate piping involved in the design and the cost of high alloy materials would be substantial. The internal insulation effort recommended involves analysis, laboratory verification, pilot installation verification, and pursuit of code acceptance. The concept to be pursued will involve expansion joints as well as internally insulated piping.

The major PC furnace operation identified as requiring specific R&D is the controlling and equalization of dry bottom PC absorption rates via the mechanism of flue gas recirculation. It is believed that this can be demonstrated during the Phase II portion of the program by the installation of absorption probes in an existing pulverized coal furnace, and the operation of that furnace with varying degrees of flue gas recirculation. Identification of an appropriate steam boiler installation and obtaining the cooperation of its operators for this testing may present a challenging problem. It may be necessary to piece together the evidence on the basis of results from several furnaces, each covering a portion of the operating region. The actual testing, however, can be accomplished in a short time, perhaps as little as a week in each instance. This effort is fundamental to the concept and would be accomplished early in Phase II.

While furnace absorption rate control is the only major R&D specifically identified relative to PC furnace operations, it will be prudent to conduct experimentation and collect data during the fire side metal corrosion program and during all laboratory and pilot operations to confirm that performance is adequate in all other areas of PC furnace and heat exchanger operations, i.e., cleanability, erosion, etc.

Analyses and design refinements are recommended during the early phase of the R&D program. The first objective is to define with more certainty the economically viable working fluid temperature and composition for the all-metal dry bottom PC combustor/heat exchanger concept. On completion of that definition further analyses and design refinement effort would be undertaken to advance to the stage beyond preliminary design. The preparation of "setting drawings" is planned. These drawings provide a higher level of detail on enclosure and heating surface arrangements, refractories, insulation, casing, support arrangements, manifolding, interconnecting piping, relief valve locations, burner size and locations, etc. Their preparation will require coming to grips with many of the detailed design problems of the installation and provide proper preparation for undertaking of the detailed design and fabrication of the pilot installation during Phase III.

The overall cost of the Phase II plus Phase III R&D program is estimated to be about $20 million. The Phase II costs of about $3 million are detailed in Section 3.1.2, which follows. The Phase III costs of about $17 million are based upon designing and installing a 35 MWe combustor/heat exchanger. All directly related auxiliaries are included, i.e., fans, pulverizers, soot blowers, etc.

Design and development effort on the combustor/heat exchanger is also included. However, design, development and fabrication costs of the balance of plant equipment, i.e., turbomachinery, piping, electrical, etc., are excluded. These latter costs are assumed to be chargeable to the equipment being developed, or to the product KWH and/or process heat. Also excluded are the costs of fuel and operating labor. These direct operating costs are assumed chargeable to the product KWH/process heat.

3.1.2 Phase II R&D Plan

An outline of the content, timing, and estimated costs of the tasks of Phase II is presented in Table 3.1.4. It is estimated that all this effort can be satisfactorily completed within the three-year time period allocated to the Phase II R&D effort.

TABLE 3.1.4. PHASE II R&D PLAN - 1550 F DRY BOTTOM PC COMBUSTOR/HEX

R&D Activity	Years			
	1	2	3	KS
1. <u>Metals - fire side corrosion</u>				1000
Technology review, coordinate with on-going R&D	▭			
Analysis & selection of candidate metals for test	▭			
Development plan, wall and convection tubes in existing environments	▭			
Development plan, walls & convection tubes in modified fire side environments	▭			
Testing & facility design & procurement	▭			
Testing in several boilers with several coals	▭	▭	▭	
Supporting laboratory testing	▭	▭	▭	
Results analysis			▭	
Define acceptable metals for each environment & temperature zone			▭	
2. <u>Metals - working fluid side corrosion</u>				125
Technology review, coordinate with on-going R&D	▭			
Development plan, He/O_2, He/CO_2/O_2 mixtures	▭			
Sample & test fixture procurement	▭			
Laboratory testing - corrosion effects - confirm conductance	▭			
Results analysis	▭	▭		
Define acceptable metals/working fluids combinations		▭		
3. <u>Internally insulated piping</u>				500
Technology review, coordinate with on-going R&D	▭			
Development plan	▭			
Hardware & test fixture design & procurement	▭			
Laboratory testing & development	▭	▭		
Results analysis - definition of adequate designs		▭		
4. <u>Boiler & Pressure Vessel Code Acceptance - New Metals</u>				120
Plan, consultant acquisition, alloy mfr coordination	▭			
Code case preparations	▭			
Code case submittals & pursuit	▭	▭	▭	
5. <u>PC Furnace Operation - Absorption rate control via EGR</u>				300
Technology review & analysis	▭			
Program development plan	▭			
Identify & obtain cooperation re test boilers	▭			
Prepare radiation instrumentation	▭			
Conduct tests (not continuous)	▭	▭		
Analysis results - EGR effects & low cycle fatigue		▭		
Define design procedures		▭		
6. <u>Analysis & Design Refinement</u>				875
Analyze to optimize rated operation requirements, working fluid composition, temperature, pressures	▭			
Analyze to optimize circuitry, surface arrangement, alloy applications, control capability, etc. Resolve questions re relative expansions, thermal strains, low cycle fatigue, etc.	▭	▭		
Prepare setting drawings		▭	▭	
7. <u>Program Phase III Program Plan</u>			▭	30
TOTAL				2960

3.2 R&D PLAN FOR 1550 F CCGT WORKING FLUID TEMPERATURE COAL FIRED COMBUSTOR/HEAT EXCHANGER-ATMOSPHERIC FLUIDIZED BEDS

The reference design conditions selected for preliminary design synthesis are presented in Table 3.2.1. Drawings of the preliminary designs of the three types of AFB modules involved are presented in Figures 3.2.1, 3.2.2, and 3.2.3. An artist's rendition of the high pressure working fluid module is presented in Fig. 3.2.4. The key features of this preliminary design as analyzed under the Key Features task of the contract are summarized in Table 3.2.2. The R&D requirements indicated by the technology conditions disclosed by the key features analysis are summarized in Table 3.2.3 together with a projected overall program chronology. A discussion of the content of the overall R&D plan and a more detailed outline of the Phase II portion of the R&D program are presented below.

3.2.1 Overall Plan and Chronology

The overall plan and chronology of Table 3.2.3 indicates an 8-year R&D program extending from the present to the achievement of "technology readiness". The timing and nature of the program is strongly influenced by several factors:

1. The technology of fluidized bed combustion of coal and its accompanying heat exchanger technology are both in the early stages of development. Development activity is already underway in these areas in connection with steam boiler applications, but it is expected that at least three to five years of additional development will be required before that technology could be regarded as "available".
2. The heat exchange surface environment in fluidized bed combustor/heat exchangers is sufficiently different from that existing in other coal fired equipment that it will be necessary to acquire much more experimental evidence prior to commercial applications of both high and low operating temperature metals.
3. The nature of the fluidized bed combustion/heat exchange processes is such that relatively small embodiments of a particular concept will furnish significant results with respect to large scale applications of that concept. This condition is aided by the modular nature of the fluidized bed application being studied.

Table 3.2.1 NON-RECUPERATED CCGT CYCLE/STEAM BOTTOMING CYCLE

He/CO$_2$ 2-Stage Exp.(1550 F/1550 F adiab turb) 1-Stage Comp. (80 F)
Steam Comp. Ratio(12) Exp. Ratio(10.92) PR Factor (91%)
Reheat (2400 P/1050 F/1050 F) Condensing (80 F)

Heater - gas in	711.84F	388.90H	1000P	HP Turbine PR = 4.217, 975.5 P_{in}, 231.3 P_{out}, LP Turbine PR = 2.59, 223.0 P_{in}, 86.1 P_{out}, Comp. PR = 12, 83.5 P_{in}, 1002.0 P_{out}
gas out	1550.00	724.36	977	
Reheater - gas in	997.55	499.50	230.1	
gas out	1550.00	724.36	223.5	
Non-Fired				
Boiler - gas in	1168.30	567.66	85.8	
gas out	790.00	418.69	85.3	
water/steam in	676.16	1038.53	2640.	
steam out	1054.16	1494.00	2480.	
Fired				
Boiler - water in	687.06	781.98	2840.	
water/steam out	678.41	1038.53	2680.	
Economizer - gas in	790.00	418.69	85.3	
gas out	135.00	182.35	84.3	
water in	83.17	59.39	3040.	
water out	688.53	781.98	2880.	
Cooler - gas in	135.00	182.35	84.3	
gas out	80.00	164.05	83.8	
cooling water in	65.00			
cooling water out	110.00			
Fired Reheater - steam in	638.00	1322.50		
steam out	1050.00	1549.66		

		Heat Balance Based on 1 lb CCGT Gas Flow	
Heat Input	Heater	335.46	
	Reheater	224.86	
	Fired Steam Boiler	83.91	
	Fired Steam Reheater	74.30	718.53
Energy Output	Non-Fired Boiler	148.97	
	Non-Fired Economizer	236.34	
	Cooler	18.30	
	CCGT Gen. Output	154.04	156.70
	CCGT Mech. & Gen. Loss	2.66	
Steam Cycle Heat Input		543.52	
	Net Thermal Eff.	.3954	
	Generator Output	214.91	
	Lb Steam/1b Gas Flow	.32707	
Overall Cycle Efficiency		.5135	
Lb Gas Flow/Hr (376.34 MW)		3480486.	
Lb Steam Flow/Hr		1138363.	
Gas Cycle Output MW		157.13	
Steam Cycle Output MW		219.21	

TABLE 3.2.2 KEY FEATURES ANALYSIS (1550 F Working Fluid, Coal-Fired Atmospheric Fluidized Bed Combustor/ Heat Exchanger Preliminary Design)

Requirement	Feature	Evaluation			Notes
		Technology Available*	Marginally Available**	Needs R&D***	
1. Fabricability	Containment		x		Refractory walls except for carbon burn-up cells
	Heating surface	x			
2. Operability	Combustion System:				
	1650 F Beds			x	
	Carbon Burn-up Cells			x	
	Emissions Control			x	
	Load Following (low loads)			x	
	Working Fluids Temperature Control		x		
	Fireside Cleanliness		x		
3. Safety	Pressure part code compliance			x	For metals operating at over 1500 F
	Fireside explosions, fires, etc.		x		
	Turbine trip (loss of coolant			x	
4. Durability	Metals			x	
	Refractory walls		x		
	Casing, insulation, etc.	x			
5. Maintainability			x		
6. First Cost	Modularization		x		
7. Operating Cost	Fuel			x	
	Other consumables			x	
	Manpower			x	
	Maintenance		x		

* - Generally acceptable solutions at hand.

** - Some doubt or dissatisfaction

*** - Positive needs identified

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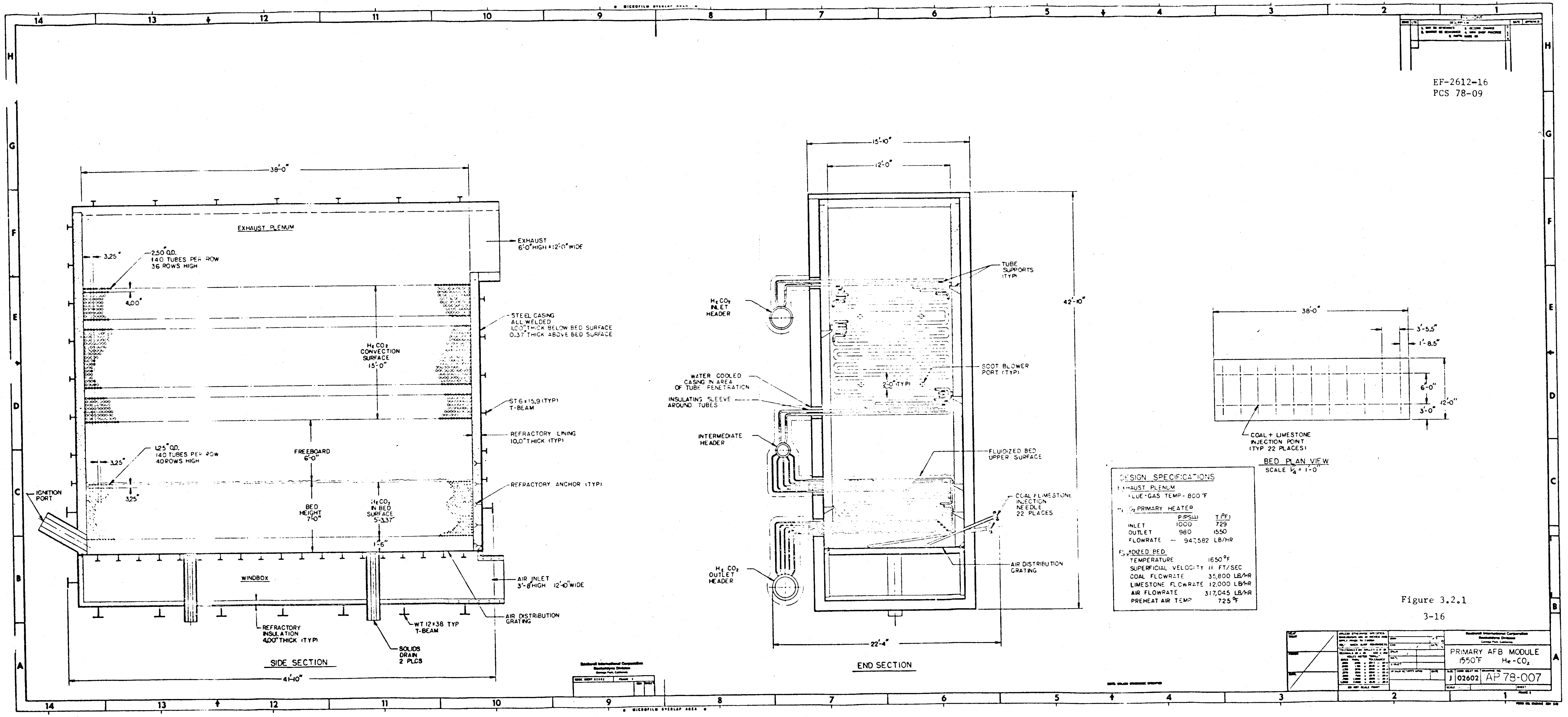
PCS 78-09



DESIGN SPECIFICATIONS

EXHAUST PLENUM

FLUE-GAS TEMP - 800°F

He CO2 PRIMARY HEATER

	P (PSIA)	T (°F)
INLET	1000	729
OUTLET	980	1550

FLOWRATE — 947,582 LB/HR

FLUIDIZED BED

TEMPERATURE	1650°F
SUPERFICIAL VELOCITY	11 FT/SEC
COAL FLOWRATE	35,800 LB/HR
LIMESTONE FLOWRATE	12,000 LB/HR
AIR FLOWRATE	317,045 LB/HR
PREHEAT AIR TEMP	725°F

Figure 3.2.1

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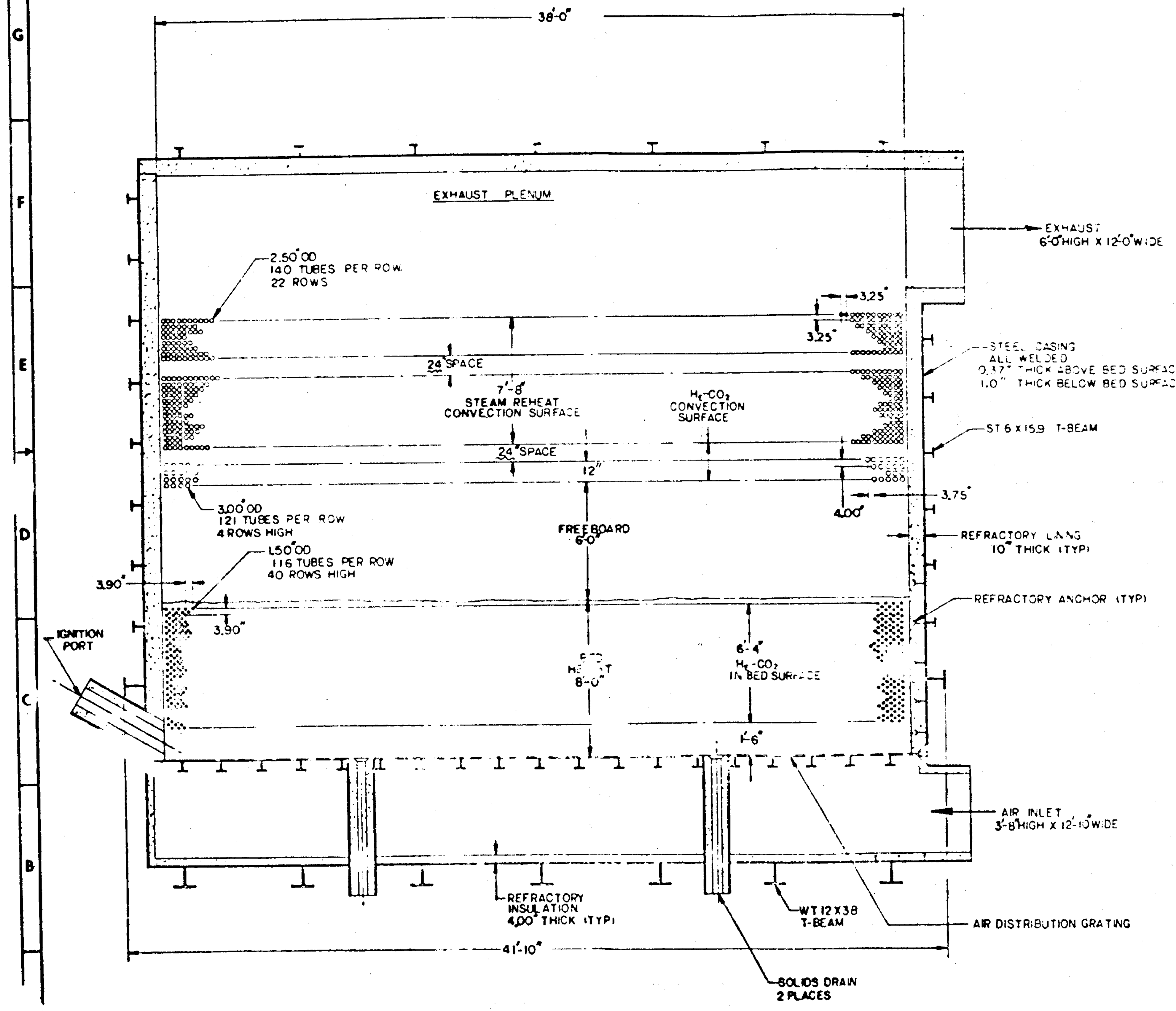

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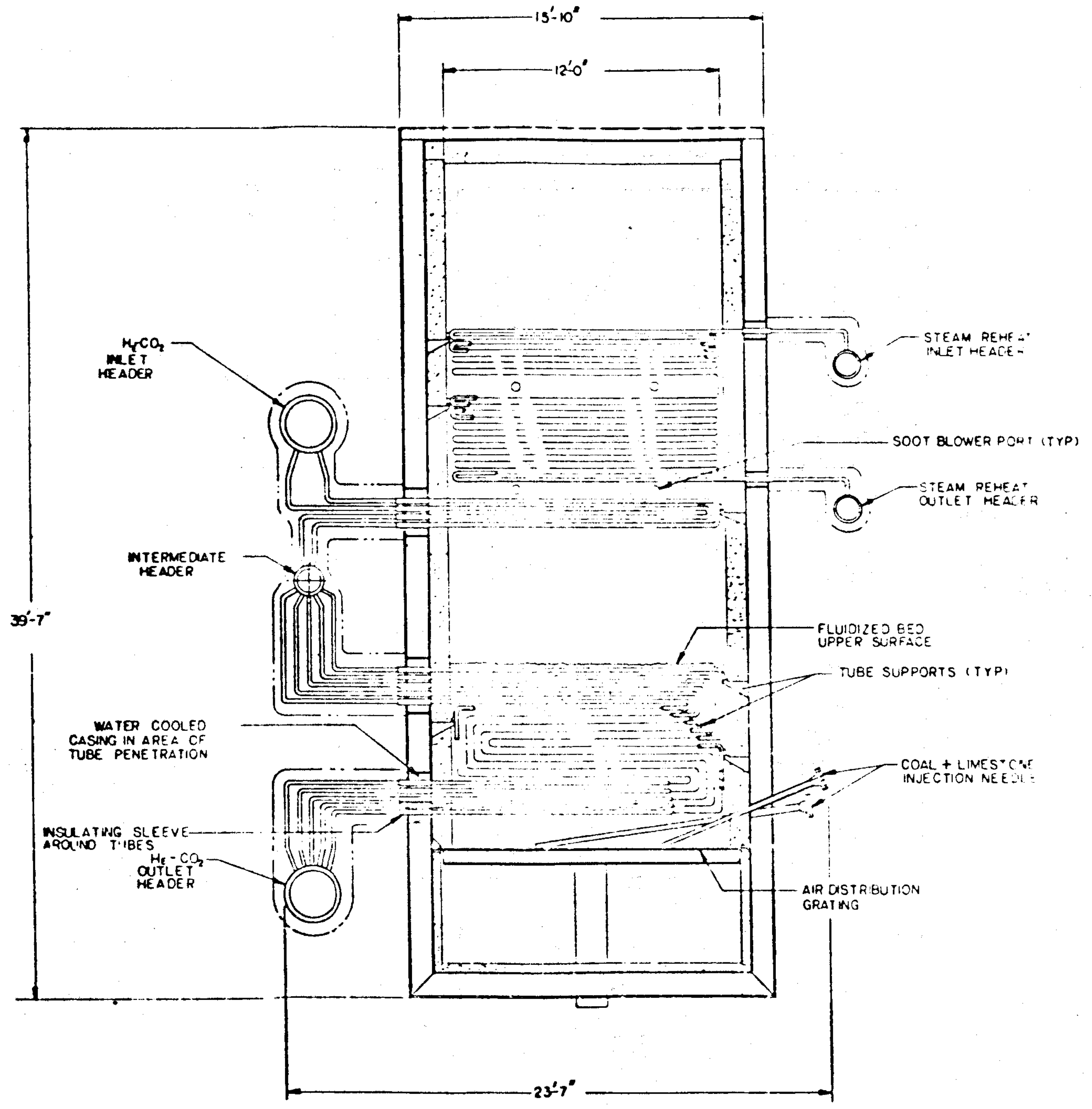

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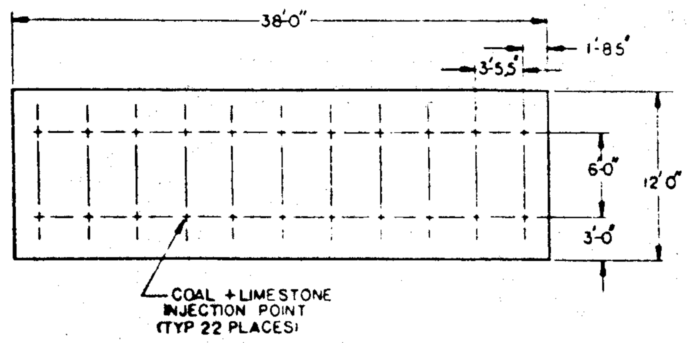


BED PLAN VIEW
SCALE $\frac{1}{4}$" = 1'-0"

DESIGN SPECIFICATIONS

EXHAUST PLENUM
FLUE GAS TEMP 800 °F

STEAM REHEATER

	P(PSIA)	TEMP (°F)
IN	480	638
OUT	432	1050
FLOWRATE	285,061 LB/HR	

H_2CO_2 REHEAT

	P(PSIA)	TEMP (°F)
IN	227	951
OUT	220	1550
FLOWRATE	947,582 LB/HR	

FLUIDIZED BED

TEMPERATURE	1650 °F
SUPERFICIAL VELOCITY	12 FT/SEC
COAL FLOWRATE	32,170 LB/HR
LIMESTONE FLOWRATE	10,782 LB/HR
AIR FLOWRATE	284,901 LB/HR
PREHEAT AIR TEMP	725 °F

Figure 3.2.2

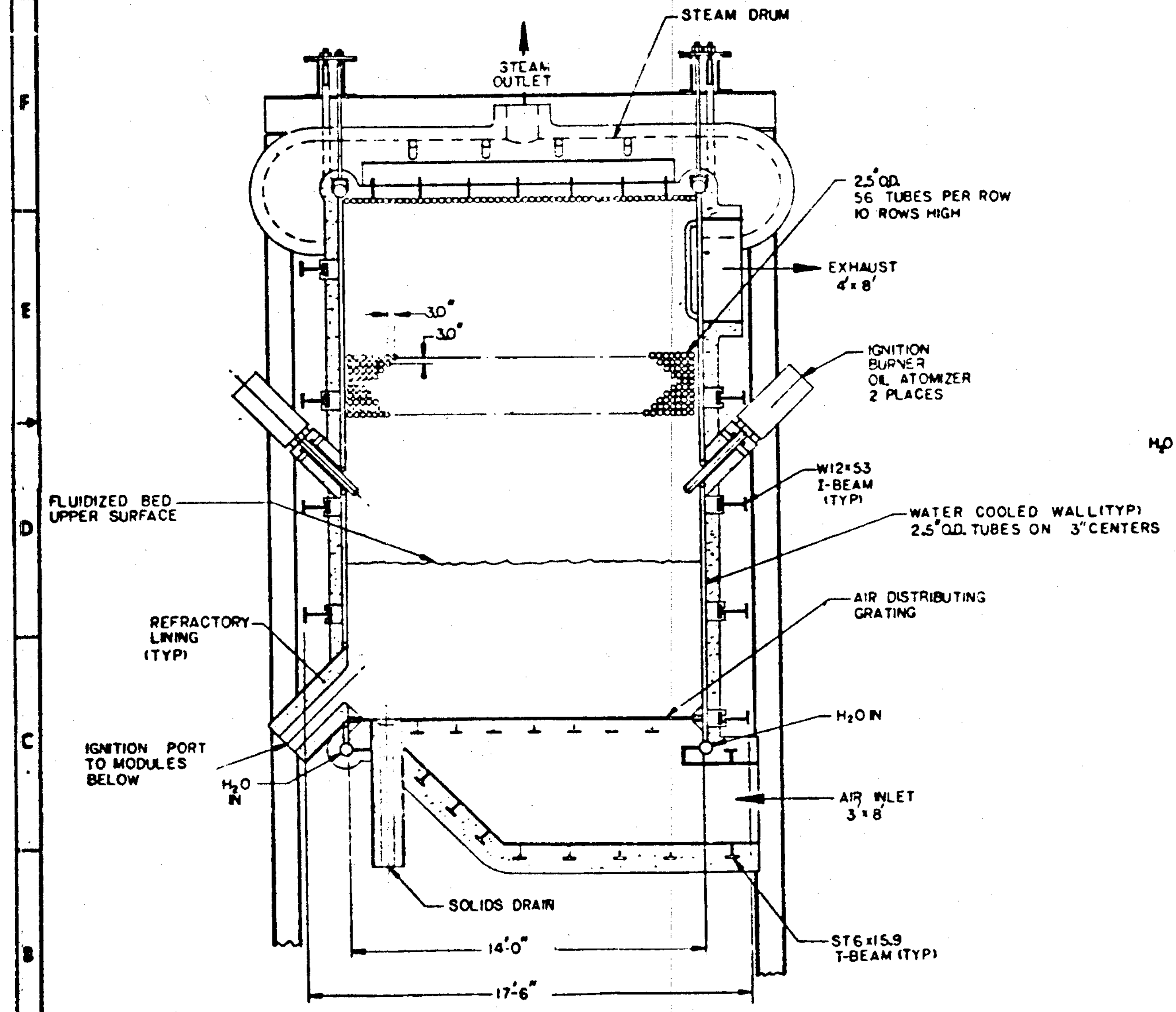
3-16a

Rockwell International Corporation
Rocketdyne Division

LOW PRESSURE
REHEAT MODULE
H_2-CO_2 & STEAM

J | 02602 | AP78-026

EF-2612-16
PCS 78-0



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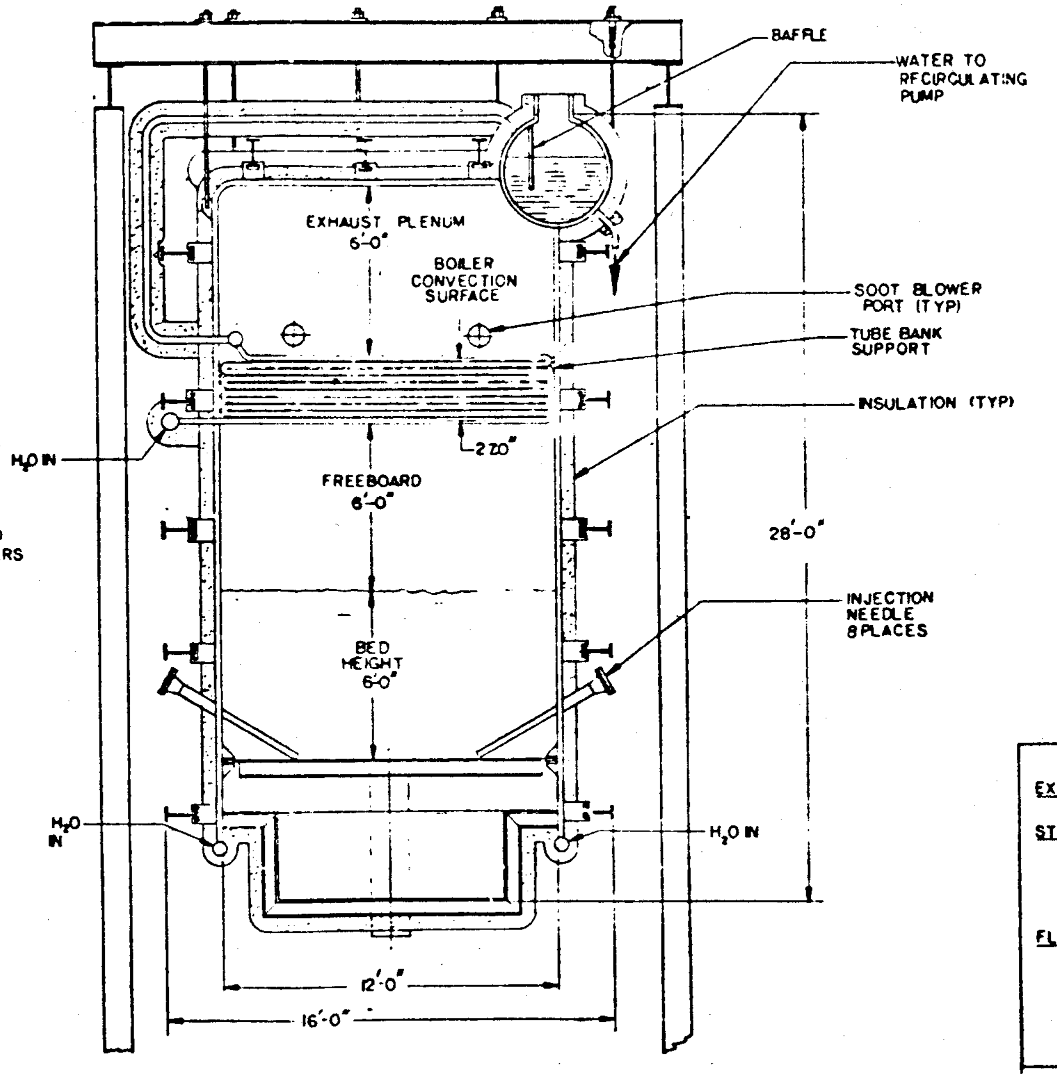

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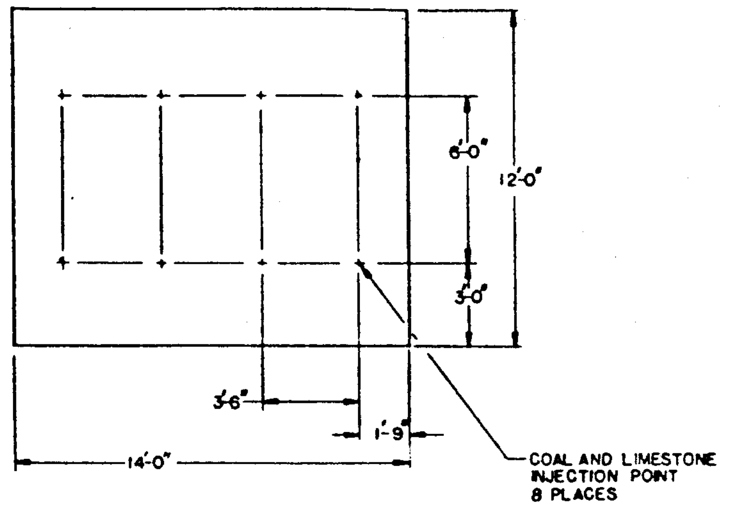


BED PLAN VIEW

DESIGN SPECIFICATIONS

EXHAUST PLENUM			
FLUE GAS TEMP			800 °F
STEAM BOILER			
	P (PSIA)	TEMP(°F)	
IN	2,880	689	
OUT	2,720	681	
FLOWRATE			128,135 LB/HR
FLUIDIZED BED			
TEMPERATURE			2,000 °F
SUPERFICIAL VELOCITY			3.9 FT/SEC
UNBURNED CARBON FLOWRATE			2,766 LB/HR
AIR FLOWRATE			36,550 LB/HR
PREHEAT AIR TEMP			725 °F

Figure 3.2.3

Rockwell International Corporation
Rocketdyne Division
Canoga Park, California

CARBON BURNUP
CELL AFB

J 02602 AP78-032

SCALE 1/2" = 1'-0"
SHEET 1

ATMOSPHERIC FLUIDIZED BED COMBUSTOR/HEAT EXCHANGER

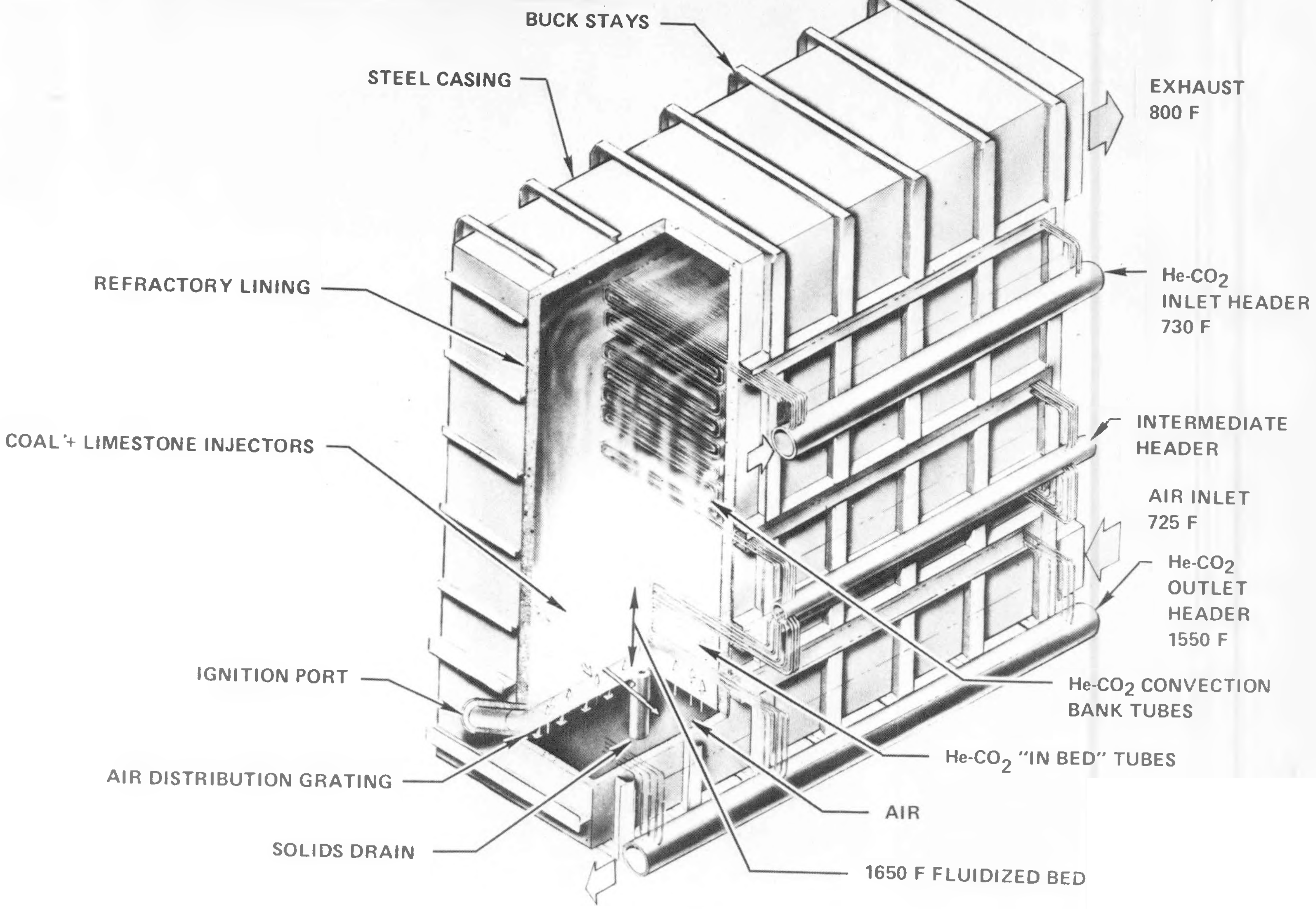


Figure 4.2.4

TABLE 3.2.3. OVERALL R&D PLAN - 1550 F FLUIDIZED BED COMBUSTOR/HEX

MAJOR REQUIRED RESEARCH	Study			Test			YEARS														
	Analysis	Design Refinement	Detail Design	Lab	Boiler	Pilot	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
							← PHASE II → Laboratory Testing, Analysis, Design Refinement			← PHASE III → Pilot design, fab. & erection		Pilot Operation									
Materials of Construction																					
In-bed heating surface - metal				x		x	←	—	→			←	—	→							
Convection heating surface - metal				x		x	←	—	→			←	—	→							
Surface supports - metal				x		x		←	→			←	—	→							
Refractories for bed containment						x						←	—	→							
Code acceptance of new metals	x						←	—	—	—	→										
Internally insulated interconnecting piping:																					
Technical feasibility	x			x		x	←	→				←	—	→							
Code acceptance	x								←	—	→										
1650 F Fluidized Bed Operations																					
Combustion/heat transfer/cleanliness/				x		x															
Ca:S ratio, load following/emissions				x		x	←	—	→			←	—	→							
control/carbon losses/loss of				x		x	←	—	→			←	—	→							
coolant simulation, etc.							←	—	→			←	—	→							
Analysis & Design Refinement																					
Working fluid composition temperature & pressure optimization	x						←→														
Prepare setting drawings	x	x	x				←	→													
Operational proof of complete combustor/HEX embodiment												←	—	→							

The above factors underly the rationale of the R&D program plan presented in Table 3.2.3. The plan includes a 3 year Phase II period during which analysis and design refinement effort would be conducted along with laboratory testing of those fluidized bed operations which are peculiar to the utilization of fluidized beds for CCGT heaters. These Phase II experimental programs would not endeavor to resolve all of the many unknowns of fluidized bed coal combustion/heat exchange. Rather the existing boiler related fluidized bed experimental programs would be monitored, and cooperated with, in order to obtain the necessary basic fluidized bed technology. Only the technology specifically related to CCGT operations, and not otherwise covered in the existing experimental programs, would be undertaken. This special technology would include research into fluidized bed environmental effects upon very high temperature metals, achievement of wide load range, loss of coolant simulations, etc. The plan is that the 3 year Phase II effort will suffice to obtain the necessary general fluidized bed technology from other programs plus the specific CCGT technology from this program. At the close of Phase III, it is expected that sufficient technology will be available to design, fabricate and operate a significantly sized pilot embodiment of the entire preliminary design.

The Phase III pilot operations are planned for a 5 year period, providing 2 years for design and erection, and 3 for experimental operations, modifications, and long term testing for confirmation of the design concepts. The size of the pilot installation and the makeup of its modules will depend upon circumstances existing at the time of decision. If a cogeneration application is available a complete full-size installation of perhaps 25 to 50 MWe capacity would be feasible, consisting of one scaled down module each of the high pressure, reheat, and carbon burnup modules. If a pilot installation has no application other than providing an experimental test bed, then a single scaled down version of the high pressure modules appears adequate.

The overall cost of a minimum eight-year R&D program is estimated to be about $15 million. The $3.7 million cost of the Phase II program is detailed in Section 3.2.2, which follows. The Phase III cost of about $11 million is based upon designing and installing a 15 MW module for a cogeneration application. All directly related combustor/HEX auxiliaries are included -- fans, controls, coal crushing and feeding, etc. Design and development effort on the combustor/HEX itself are also included. Not included are design, fabrication and development of the balance of plant equipment. These costs are assumed to be chargeable to the BOP equipment being developed, or to the electrical and heat energy generated. Also excluded are the costs of fuel and operating labor, again chargeable to the energy produced.

3.2.2 Phase II R&D Plan

An outline of the content, timing and estimated costs of PHase II is presented in Table 3.2.4.

TABLE 3.2.4. PHASE II R&D PLAN - 1550 F FLUIDIZED BED COMBUSTOR/HEX R&D ACTIVITY

R&D Activity	Years 1	2	3	$K
1. METALS - FIRESIDE CORROSION				1200
Technology review, coordinate with on-going R&D	▬			
Analysis and selection of candidate metals for test	▬			
Development plan, in-bed and above-bed tubes in existing beds and lab beds	▬			
Test rig and facility designs and procurement	▬			
Testing in several beds with several coals and several stones	▬	▬	▬	
Supporting laboratory testing	▬	▬	▬	
Results analysis			▬	
Define acceptable metals for each environment & temperature zone			▬	
2. METALS - WORKING FLUID SIDE CORROSION				125
Technology review, coordinate with on-going R&D	▬			
Development plan, air, N$_2$, He/CO$_2$/O$_2$ mixtures	▬			
Sample and test fixture procurement	▬			
Laboratory testing - corrosion effects - confirm conductance	▬			
Results analysis	▬	▬		
Define acceptable/working fluids combinations		▬		
3. INTERNALLY INSULATED PIPING				500
Technology review, coordinate with on-going R&D	▬			
Development plan	▬			
Hardware and test fixture design and procurement	▬			
Laboratory testing and development	▬	▬		
Results analysis - definition of adequate design		▬		
4. BOILER & PRESSURE VESSEL CODE ACCEPTANCE - NEW METALS				120
Plan, consultant acquisition, alloy manufacturer coordination	▬			
Code case preparations	▬			
Code case submittals and pursuit	▬	▬	▬	
5. 1650 F FLUIDIZED BED OPERATIONS				750
Technology review and analysis	▬			
Monitor and coordinate with existing R&D programs	▬	▬	▬	
Prepare development plan for specific CCGT efforts	▬			
Design and procure hardware, prepare test facility	▬			
Conduct tests - laboratory scale	▬	▬	▬	
Analyze results		▬	▬	
Define design procedures			▬	
6. ANALYSIS AND DESIGN REFINEMENT				975
Analyze to optimize rated operating requirements, working fluid composition, temperature, pressures	▬			
Analyze to optimize circuitry, surface arrangement, alloy applications, control capability, etc., resolve questions re relative expansions, thermal strains, low cycle fatigue, etc.	▬	▬		
Prepare setting drawings		▬	▬	
7. PREPARE PHASE II PROGRAM PLAN			▬	30
TOTAL				3700

3.3 R&D PLAN - 1750 F/1550 F CCGT WORKING FLUID TEMPERATURE COAL-FIRED COMBUSTOR/ HEAT EXCHANGER - MIXED MODE

The reference design conditions selected for preliminary design synthesis are presented in Table 3.3.1, a drawing of the preliminary design of the highest temperature modules is presented in Fig. 3.3.1, and an artist's rendition of the highest temperature design is presented in Fig. 3.3.2. The key features of this preliminary design as analyzed under the Key Features task of the contract are summarized in Table 3.3.2.

The R&D requirements indicated by the technology conditions disclosed by the Key Features analysis are summarized in Table 3.3.3, along with a projected overall chronology. A discussion of the content of the planned R&D program is presented below.

3.3.1 Overall Plan and Chronology

The overall plan and chronology of Table 3.3.3 shows a 12-year R&D program extending from the present to the achievement of technology readiness. The timing and nature of the program is strongly influenced by the factors listed below:

1. The mixed mode combustion technology is an extension of the fluidized bed combustion technology required for the 1550 F CCGT working fluid cycles. Added combustion capabilities are required in the areas of 2000 F bed temperature operations for heat input to the highest temperature working fluids, the handling of dust-contaminated gases by the distributor plates of the low-temperature beds, and the absorption by the low-temperature beds of sulphur oxides in the flue gases leaving the high-temperature beds. Thus all of the fluidized bed technology discussed in Section 3.2, plus extensions to that technology, will be required for satisfactory operation of the 1750 F working fluid preliminary design concept.

Table 3.3.1. NON-RECUPERATED CCGT CYCLE/STEAM BOTTOMING CYCLE

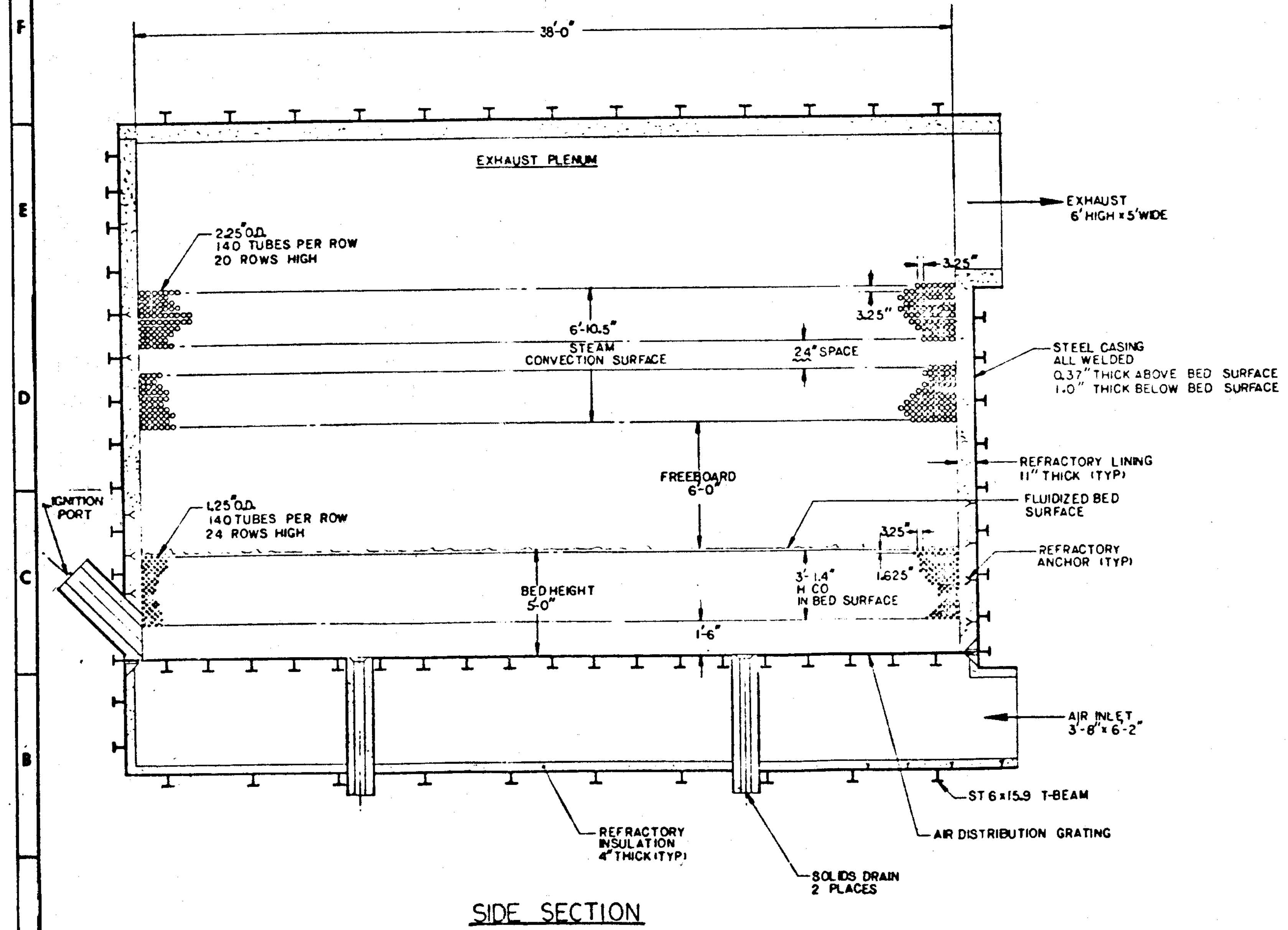
He/CO_2 2-Stage Exp.(1750 F cooled/1550 F adiab) 1-Stage Comp. (80 F)
Comp. Ratio (12) Exp. Ratio (10.92) PR Factor (91%)
Steam Reheat (2400P/1050F/1050F) Condensing (80 F)

Heater - gas in .965 lb	712.05F	388.98H	1000P	HP turbine PR=3.778 975.5 P_{in} 258.21 P_{out}, LP turbine PR=2.89, 248.83 P_{in} 86.1 P_{out}, 85.8 comp. PR=12, 83.5 P_{in} 1002 P_{out}
gas out	1750.00	808.24	977	
Reheater - gas in	1170.70	568.63	257.01	
gas out	1550.00	724.36	249.33	
Non-Fired				
Boiler - gas in	1128.46	551.64	85.8	
gas out	790.00	418.69	85.3	
water/steam in	678.57	1087.51	2640.	
steam out	1054.16	1494.00	2480.	
Fired				
Boiler - water in	687.06	781.98	2840.	
water/steam out	681.93	1087.51	2680.	
Economizer - gas in	790	418.69	85.3	
gas out	135	182.35	84.3	
water in	83.17	59.39	3040.	
water out	688.53	781.98	2880.	
Cooler - gas in	135	182.35	84.3	
gas out	80	164.05	83.8	
cooling water in	65			
cooling water out	110			
Fired Reheater - steam in	638	1322.50		
steam out	1050	1549.66		

Heat Balance Based on 1 lb CCGT Gas Flow

Heat Input	Heater	404.58	
	Reheater	155.73	
	Fired Steam Boiler	99.93	
	Fired Steam Reheater	74.30	734.54
Energy Output	Non-Fired Boiler	132.96	
	Non-Fired Economizer	236.34	
	Cooler	18.30	
	CCGT Gen. Output	169.78	172.72
	CCGT Mech. & Gen. Loss	2.94	
	Steam Cycle Heat Input	543.53	
	Net Thermal Eff.	.3954	
	Generator Output	214.91	
	Lb Steam/1b Gas Flow	.32707	
	Overall Cycle Efficiency	.5237	
	Lb Gas Flow/Hr (376.34 MW)	3.338078×10^6	
	Lb Steam Flow/Hr	1.091785×10^6	
	Gas Cycle Output MW	166.09	
	Steam Cycle Output MW	210.25	

EF-2612-16
PCS 78-09



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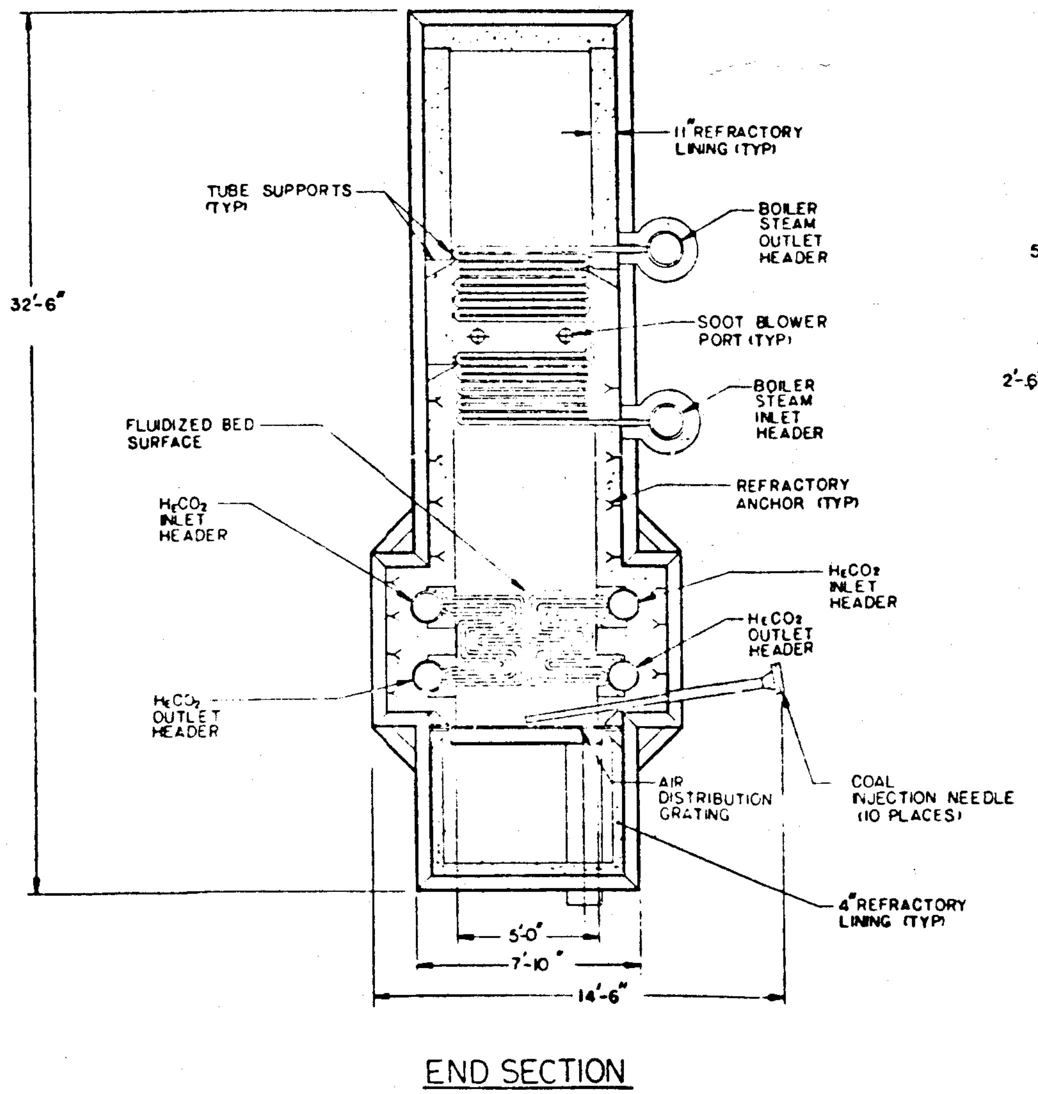

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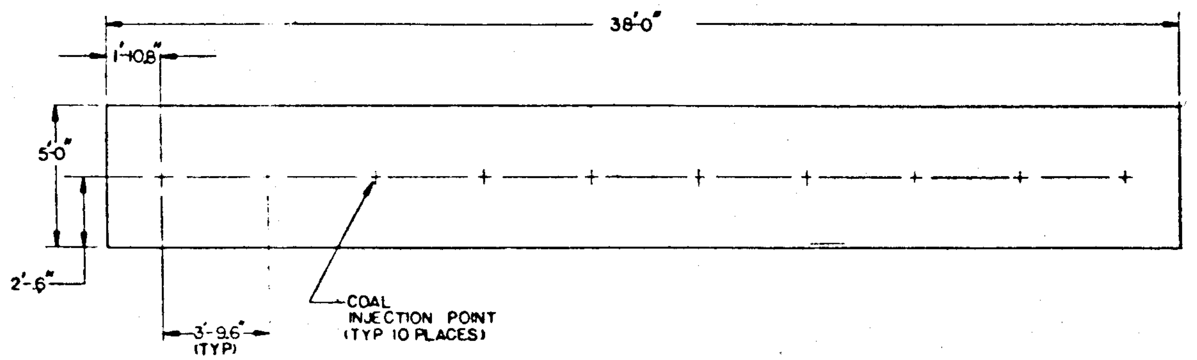

DESIGN SPECIFICATIONS

EXHAUST PLENUM		
FLUE GAS TEMP		800 °F
BOILER STEAM		
	P (PSIA)	TEMP (°F)
IN	2840	687
OUT	2680	682
FLOWRATE		90,982 LB/HR
H_eCO_2		
	P (PSIA)	TEMP (°F)
IN	985	1550
OUT	980	1750
FLOWRATE		835,000 LB/HR
FLUIDIZED BED		
TEMPERATURE		2,000 °F
SUPERFICIAL VELOCITY		12 FT/SEC
COAL FLOWRATE		14,000 LB/HR
AIR FLOWRATE		120,000 LB/HR
PREHEAT AIR TEMP		725 °F

Figure 3.3.1

3-23

Rockwell International Corporation
Rocketdyne Division
Canoga Park California

2000 °F FLUIDIZED BED
(F B) MODULE

J 02602 AP78-035

SCALE 1/2 = 1'-0"

DO NOT SCALE PRINT

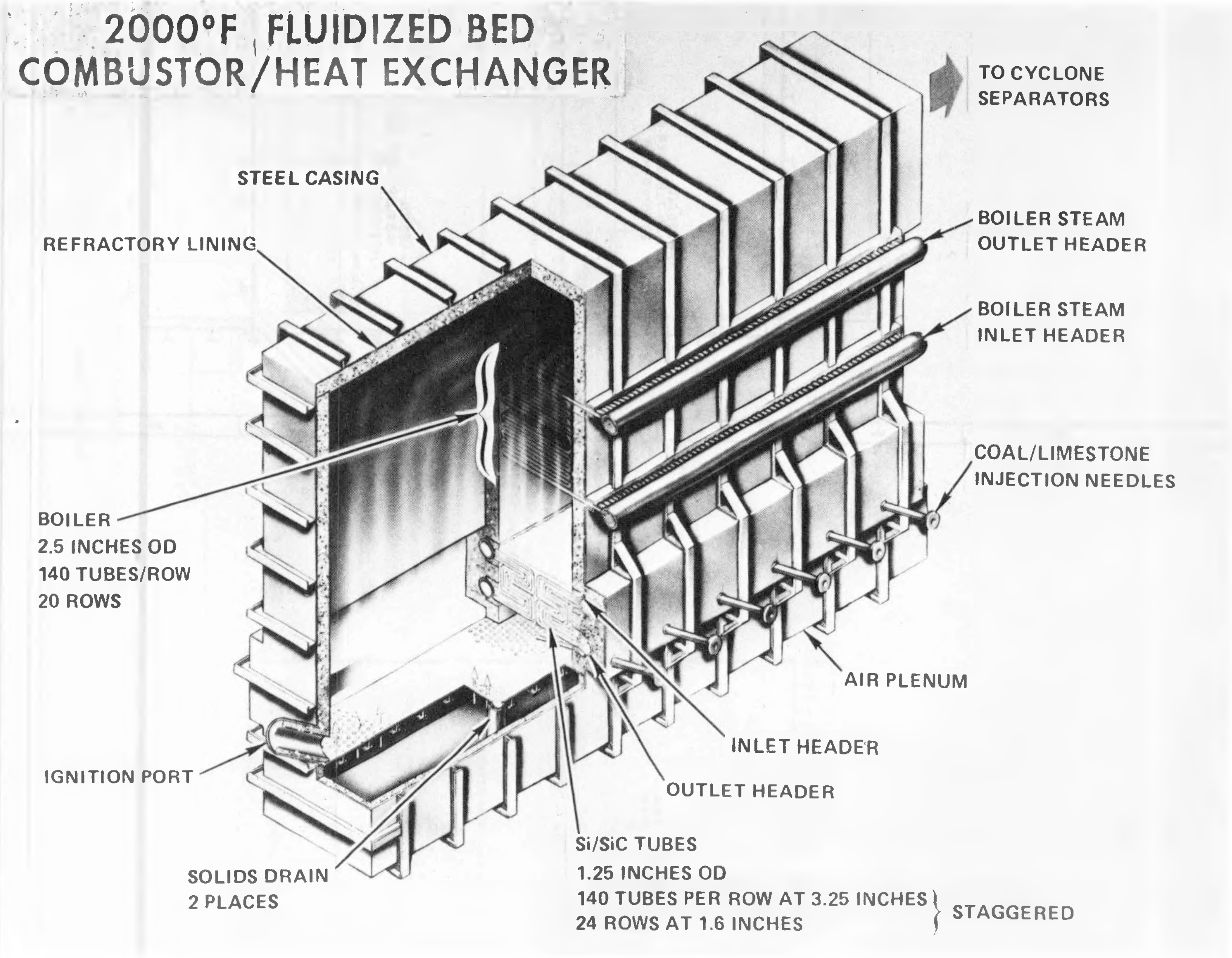
2000°F FLUIDIZED BED COMBUSTOR/HEAT EXCHANGER
TO CYCLONE SEPARATORS
STEEL CASING
REFRACTORY LINING
BOILER STEAM OUTLET HEADER
BOILER STEAM INLET HEADER
COAL/LIMESTONE INJECTION NEEDLES
BOILER
2.5 INCHES OD
140 TUBES/ROW
20 ROWS
AIR PLENUM
INLET HEADER
IGNITION PORT
OUTLET HEADER
Si/SiC TUBES
1.25 INCHES OD
140 TUBES PER ROW AT 3.25 INCHES
24 ROWS AT 1.6 INCHES
STAGGERED
SOLIDS DRAIN
2 PLACES

Figure 3.3.2

TABLE 3.3.2 KEY FEATURES ANALYSIS (1750 F Working Fluid Coal-Fired Mixed Mode Combustor/ Heat Exchanger Preliminary Design)

Requirement	Feature	Evaluation			Notes
		Technology Available*	Marginally Available**	Needs R&D***	
1. Fabricability	Containment		x		
	Heating Surface - Ceramics			x	A new technology
	Metals	x			
2. Operability	Combustion System:				
	2000 F Beds			x	
	1650 F Beds			x	
	Carbon burn-up cells			x	
	Emissions Control			x	Mixed mode
	Load Following (low loads)			x	
	Working Fluids Temperature Control		x		
	Fireside Cleanliness		x		
3. Safety	Pressure Part Code Compliance			x	Brittle ceramics
	Fireside Explosions, Fire, etc.		x		
	Turbine Trip (loss of coolant)			x	
4. Durability	Ceramic Heat Exchanger Surface			x	
	Metals			x	
	Refractory Walls		x		
	Casing, Insulation, etc.	x			
5. Maintainability			x		
6. First Cost	Modularization		x		
7. Operating Cost	Fuel			x	
	Other Consumables			x	
	Manpower			x	
	Maintenance		x		

* - Generally acceptable solutions at hand

** - Some doubts or dissatisfaction

*** - Positive needs identified

TABLE 3.3.3. OVERALL R&D PLAN - 1750 F MIXED MODE COMBUSTOR/HEX

	Study			Test			YEARS														
MAJOR REQUIRED RESEARCH	Analysis	Design Refinement	Detail Design	Lab	Boiler	Pilot	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
							← Phase II - Ceramic technology development, lab-scale AFB research, design refinement	—	—	—	→	← Phase III	—	—	—	—	—	→			
												← Pilot Design fab and erection	—	→	← Pilot Operation	—	—	→			
Materials of Construction																					
Same as 1550 F AFB Plus:																					
Ceramic Technology Development	x	x	x	x		x	←	—	—	—	—	—	—	—	—	—	—	→			
Ceramic Pressure Part Code Acceptance	x									←	—	—	—	—	—	—	—	→			
1750 F Internally Insulated Piping:																					
Technical feasibility	x			x		x	←	→													
Code acceptance	x								←	—	→										
Fluidized Bed Operations - same as 1550 AFB except:																					
Add 2000 F bed operations				x		x	←	→							←	—	—	→			
Add "mixed mode" condition to 1650 F bed operations				x		x	←	→							←	—	—	→			
Analysis & Design Refinement																					
Working fluid pressures, temperature and composition optimization	x						←→														
Optimize functional design	x	x					←	—	—	→											
Prepare setting drawings	x	x	x							←	→										
Operational proof of complete combustor/HEX embodiment															←	—	—	→			

2. All of the metals development technology discussed in Section 3.2 is also required for satisfactory operation of the 1750 F preliminary design concept.

3. All heating surface that contains working fluids at temperatures higher than 1550 F is fabricated of ceramic materials. An extensive and time-consuming development program is required to bring all aspects of ceramic heat exchanger technology, i.e., manufacture, quality control, assembly and joining, operation, durability, maintainability, and design procedures, to a condition in which design and fabrication of a significantly sized pilot installation could be undertaken.

The rationale underlying the program plan presented in Table 3.3.3 is influenced by the above-listed factors. It visualizes a five-year "Phase II" program which is paced by the effort required for the development of the necessary ceramic technology. The specialized fluidized bed operational capabilities required for success of the mixed mode concept would be evaluated on a laboratory scale during the early portions of Phase II, so as to determine whether the mixed mode concept is fundamentally viable. The necessary additional fluidized bed and metals development tasks, which are similar in nearly all respects to those outlined under Section 3.2 for the 1550 F AFB preliminary design, would be conducted during the remainder of the Phase II program. The object would be to have the ceramic, metals, and fluidized bed technologies checked out and available for pilot installation design and the start of Phase III by the end of the fifth year.

The Phase III effort has been allocated seven years and is expected to be paced again by the development problems of the ceramic heat exchanger surface. The nature of the pilot installation would depend upon the opportunities available when Phase III is funded. It might consist of a complete assembly of modules of small scale to satisfy the requirements of a 25- to 50-MWe cogeneration application. On the other hand, if the module were intended solely to confirm operation prior to a full-scale utility operation, it might consist of a 5- by 12-foot, 2000 F module and a 12- by 12-foot 1650 F module.

The R&D plan of Table 3.3.3 could be conducted entirely separately from the development of other preliminary designs. However, it seems more likely that development of the 1550 F CCGT working fluid temperature fluidized bed concept preliminary designs would be first undertaken, and then the 1750 F capability added with later work.

The estimated $15.2 million cost of the five-year Phase II program is detailed in Section 3.3.2, which follows. These costs include about $3 million in metals and fluidized bed R&D which is also provided in the 1550 F AFB combustor/HEX R&D program of Section 3.2. Assuming that the 1750 F mixed mode program follows the 1550 F program and utilizes the 1550 F results and hardware for support, its total costs are estimated to be $33 million (15 minus 3 equals 12 million for Phase II plus 21 million for Phase III). These costs include design and installation of directly related combustor/HEX equipment plus all development of the combustor/HEX. As with previous estimates, the design, fabrication and development of balance of plant equipment is not included, nor is the fuel and operating labor.

3.3.2 Phase II R&D Plan

An outline of the timing, content and estimated costs of Phase II is presented in Table 3.3.4.

TABLE 3.3.4. PHASE II R&D PLAN - 1750 F MIXED MODE COMBUSTOR/HEX

R&D Activity	Years					$K
	1	2	3	4	5	
1. Ceramics - All aspects of design, fabrication & utilization						10,000
Technology review, coordinate with on-going R&D						
Development plans; basic materials; manufacture & QC; characterization for strength, environmental compatibility; assembly & maintainability; code acceptance; design procedures						
Manufacturing facilities acquisition						
Test rig & test facilities & samples acquisition						
Experimentation (manufacture, assembly, mechanical operations strength, temperature effects, physical characteristics, environmental effects - fluidized bed, working fluids						
Results analysis						
Define available properties						
Define design procedures						
2. Metals - Fireside Corrosion						1,200
Technology review, coordinate with on-going R&D						
Analysis & selection of candidate metals for test						
Development plan, in-bed & above bed, tubes in existing beds & lab beds						
Test rig & facility designs & procurement						
Testing in several beds with several coals & several stones						
Supporting laboratory testing						
Results analysis						
Define acceptable metals for each environment & temperature zone						
3. Metals - Working Fluid Side Corrosion						125
Technology review, coordinate with on-going R&D						
Development plan, air, N_2/ $He/CO_2/O_2$ mixtures						
Sample & test fixture procurement						
Laboratory testing - corrosion effects - confirm conductance						
Results analysis						
Define acceptable metals/working fluids combinations						
4. Internally Insulated Piping						600
Technology review, coordinate with on-going R&D						
Development plan						
Hardware & test fixture design & procurement						
Laboratory testing & development						
Results analysis - definition of adequate design						
5. Boiler & Pressure Vessel Code Acceptance - new metals						120
Plan, consultant acquisition, alloy mfr coordination						
Code case preparation						
Code case submittal & pursuit						
6. Boiler & Pressure Vessel Code Acceptance - Ceramics						250
Plan, consultant acquisition, ceramics mfr coordination, code committee contacts & coordination						
Code case preparations						
Code case submittal & pursuit						
7. 2000 F Fluidized Bed Operations						750
Technology review & analysis						
Monitor & coordinate with existing R&D programs						
Prepare development plan for mixed mode concepts						
Design & process hardware, prepare test facility						
Conduct laboratory-scale tests						
Analyze results						
Define design procedures						

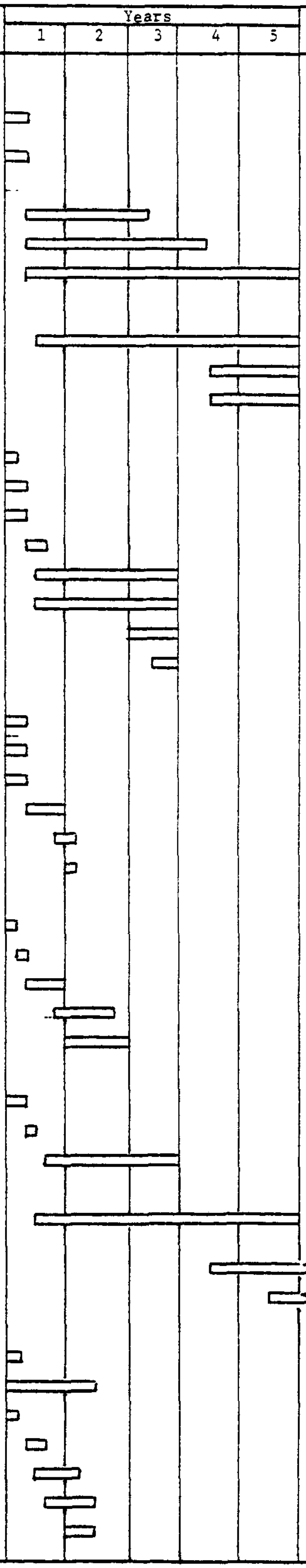

TABLE 3.3.4. PHASE II R&D PLAN - 1750 F MIXED MODE COMBUSTION/HEX (Concluded)

R&D Activity	Years					$K
	1	2	3	4	5	
8. <u>1650 F Fluidized Bed Operations</u>						800
Technology review & analysis	▬					
Monitor & coordinate with existing R&D programs	▬	▬	▬			
Prepare development plan for specific CCGT efforts	▬					
Design & procure hardware, prepare test facility	▬					
Conduct tests - laboratory scale	▬	▬	▬			
Analyze results		▬	▬			
Define design procedures			▬	▬		
9. <u>Analysis & Design Refinement</u>						1300
Analyze to optimize rated operating requirements, working fluid composition, temperature, pressures	▬					
Analyze to optimize circuitry, surface arrangement, alloy applications, control capability, etc., resolve questions re relative expansions, thermal strains, low cycle fatigue, etc.			▬	▬		
Prepare setting drawings				▬	▬	
10. <u>Prepare Phase III Program Plan</u>					▬	50
TOTAL						15,195

3.4 R&D PLAN - 2250 F CCGT WORKING FLUID TEMPERATURE COAL-FIRED COMBUSTOR/HEAT EXCHANGER, SLAGGING CYCLONE COMBUSTOR R&D PLAN

The reference design conditions selected for the preliminary design synthesis are presented in Table 3.4.1, a drawing of the preliminary design is presented in Fig. 3.4.1, and an artist's rendition of the design is presented in Fig. 3.4.2. The key features of this preliminary design as analyzed under the Key Features task of the contract are summarized in Table 3.4.2. The R&D requirements indicated by the technology conditions disclosed by the Key Features analysis are summarized in Table 3.4.3, along with a projected overall chronology. A discussion of the content of the planned R&D program is presented below.

3.4.1 Overall Plan and Chronology

The overall plan and chronology of Table 3.4.3 shows a 12-year R&D program extending from the present to the achievement of technology readiness. The timing and nature of the program are strongly influenced by several factors:

1. A relatively long period is anticipated for the development of the necessary ceramic heat exchanger surface technology. This condition is similar to that described in 3.3.1 above, but the ceramic environment is different and presumably more severe.
2. The NOX emissions characteristics of slagging combustors, both pulverized and cyclone-fired, are presently unacceptable.

The rationale of the R&D program plan presented in Table 3.4.3 is that the length of Phase II will be paced by the time required for development of the necessary ceramic heat exchanger technology, which involves fabrication, assembly, maintainability, design procedures, durability in a slagging environment, etc. During the early portion of this period, it is

Table 3.4.1 NON-RECUPERATED BRAYTON CYCLE/STEAM BOTTOMING CYCLE

He 1-Stage Exp. (2250 F) 1-Stage Comp. (80 F) (Adiabatic)
Comp. Ratio (5) Exp. Ratio 4.55 (91%)
Steam 1 Reheat (2400 P/1050 F/1050 F Condensing (80 F)

Heater - gas in	644.06F	1368.62H	1000P	HP turbine PR=4.55
gas out	2250.	3359.98	955	950 P_{in} 208.79
Reheater - gas in	--	---		P_{out}, Comp. PR=5
gas out	--			200.8 P_{in},
Non-fired - Boiler - gas in	1096.40	1929.52	207.5	1004 P_{out}
gas out	790	1549.58	206	
water/steam in	701.38	1155.98	2640	
steam out	1054.16	1494	2480	
Fired Boiler - water in	687.06	781.98	2840	
water/steam out	704.6	1155.98	2680	
Economizer - gas in	790.	1549.98	206	
gas out	135.	737.39	203	
water in	83.17	59.39	3040	
water out	688.53	781.98	2880	
Cooler - gas in	135.	737.39	203	
gas out	80.	669.19	201.5	
cooling water in	65.			1.335614×10^6 lb/hr
cooling water out	110			
Fired reheater - steam in	638	1322.5		
steam out	1050	1549.66		

		Heat Balance Based on 1 lb. CCGT Gas Flow	
Heat Input	Heater	1991.36	
	Reheater	---	
	Fired Steam Boiler	420.38	
	Fired Steam Reheater	255.33	2667.07
Energy Output	Non-Fired Boiler	379.94	
	Non-Fired Economizer	812.19	
	Cooler	68.2	
	CCGT Generator Output	718.59	731.02
	CCGT Mech. & Gen Loss	12.43	
Steam Cycle Heat Imput		1867.84	
	Net Thermal Eff.	.3954	
	Generator Output	738.54	
	Lb Steam/lb Gas Flow	1.124	
Overall Cycle Efficiency		.5463	
Lb Gas Flow/Hr (376.34 MW)		881270.	
Lb Steam Flow/Hr.		990548.	
Gas Cycle Output MW		185.59	
Steam Cycle Output MW		190.75	

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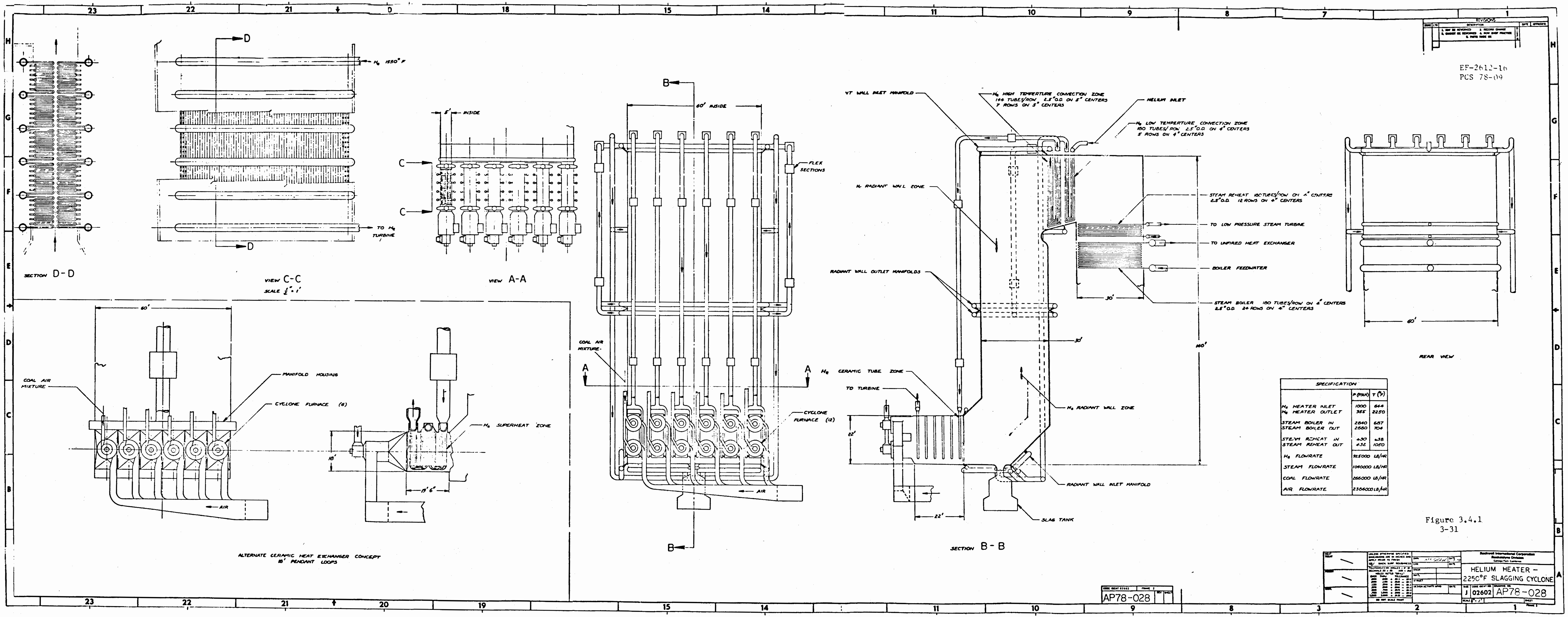

SPECIFICATION

	P (PSIA)	T (°F)
H_e HEATER INLET	1000	644
H_e HEATER OUTLET	355	2250
STEAM BOILER IN	2840	687
STEAM BOILER OUT	2680	704
STEAM REHEAT IN	430	638
STEAM REHEAT OUT	432	1050
H_e FLOWRATE	925000 LB/HR	
STEAM FLOWRATE	1040000 LB/HR	
COAL FLOWRATE	266000 LB/HR	
AIR FLOWRATE	2386000 LB/HR	

Figure 3.4.1
3-31

Rockwell International Corporation
Rocketdyne Division
Canoga Park, California

HELIUM HEATER –
2250°F SLAGGING CYCLONE

SIZE J
CODE IDENT NO. 02602
DRAWING NO. AP78-028

AP78-028

2250°F CYCLONE FIRED COMBUSTOR/HEAT EXCHANGER

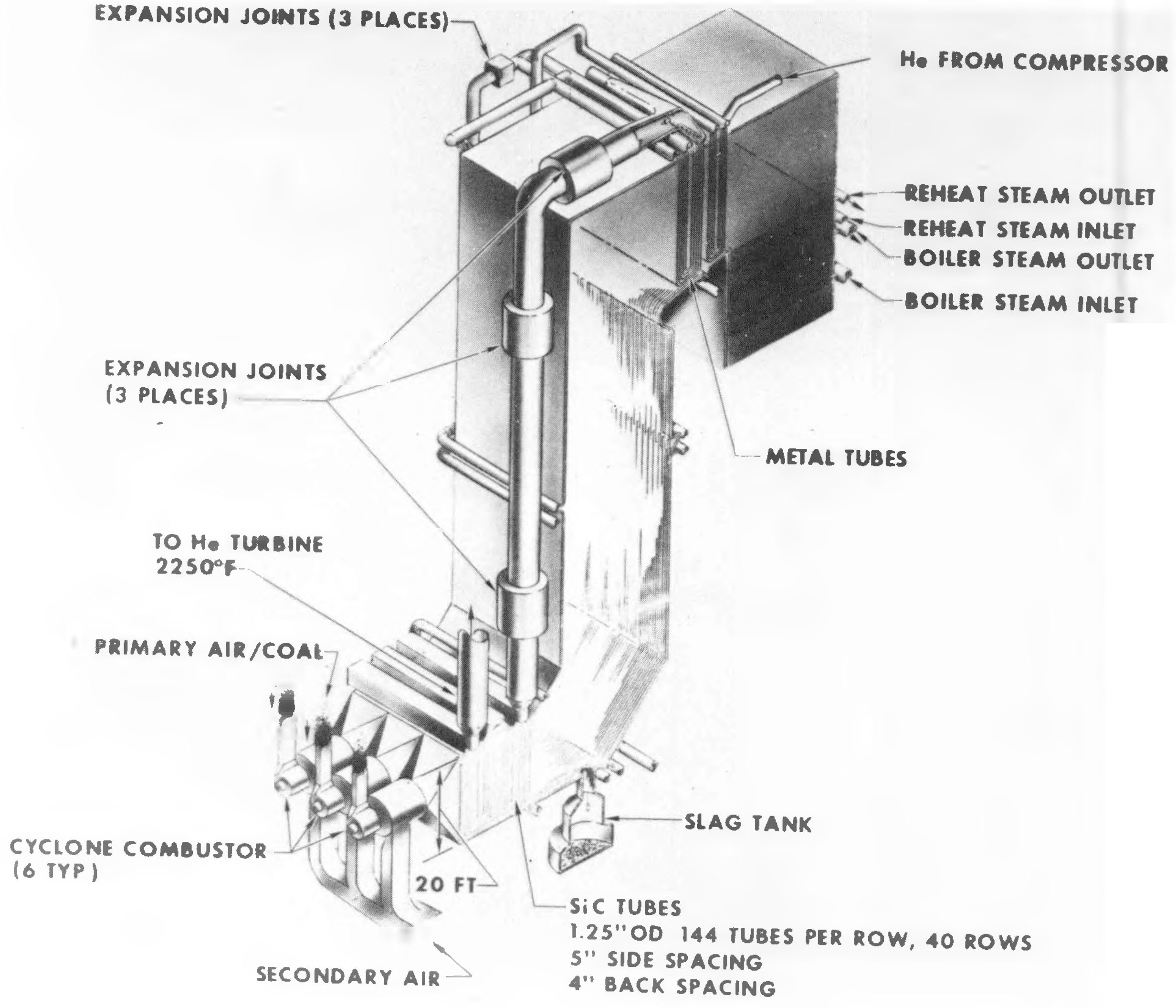

Figure 3.4.2

TABLE 3.4.2 KEY FEATURES ANALYSIS (2250 F Working Fluid Coal-Fired Atmospheric Fluidized Bed Combustor/Heat Exchanger Preliminary Design)

Requirement	Feature	Evaluation			Notes
		Technology Available*	Marginally Available**	Needs R&D***	
1. Fabricability	Containment	x			
	Convection Surface - Ceramic			x	New technology
	Metal	x			
2. Operability	Combustion System	x			
	Emissions Control		x		NOX control by ammonia reaction
	Load Following		x		
	Working Fluids Temperature Control	x			
3. Safety	Pressure Part Code Compliance			x	Ceramics
	Fireside Explosions, Fires, etc.	x			
	Turbine Trip (loss of coolant)	x			
4. Durability	Ceramic Heat Exchanger Surface			x	
	Metals - Under 1100 F	x			
	Over 1100 F			x	
	Casing Insulation, etc.	x			
5. Maintainability			x		
6. First Cost	Size and Surface	x			
	Ceramics vs Superalloys		x		
	Emissions Control			x	NOX
7. Operating Cost	Fuel	x			
	Other Consumables		x		
	Manpower	x			
	Maintenance			x	Ceramics

* - Generally acceptable solutions at hand

** - Some doubt or dissatisfaction

*** - Positive needs identified

TABLE 3.4.3. OVERALL R&D PLAN - 2250 F SLAGGING CYCLONE COMBUSTOR/HEX

MAJOR REQUIRED RESEARCH	Study			Test			YEARS														
	Analysis	Design Refinement	Detail Design	Lab	Boiler	Pilot	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
							← Phase II - ceramic technology development, laboratory & component testing, analysis, design refinement →					← Phase III →									
												← Pilot design, fab & erection →			← Pilot Operation →						
Materials of Construction																					
Ceramic technology development, 1500-2400 F, slagging environment	x	x	x	x	x	x	←	—	—	—	—	—	—	—	—	—	—	→			
Ceramic pressure part code acceptance	x									←	—	—	—	—	—	—	—	→			
Metals at >1100 F, similar to 1550 F dry bottom PC				x	x	x	←	—	—	—	—	—	—	—	—	—	—	→			
New metals code acceptance	x						←	—	—	—	→										
Slagging Cyclone Combustor Operations																					
Slagging ceramic convection surface				x	x		←	→													
NOX control					x		←	—	—	—	→	→	—	→	←	→					
Analysis & Design Refinement																					
Working fluid pressure, temperature & composition optimization	x						↔														
Optimization of functional design	x	x					←	—	→												
Prepare setting drawings	x	x	x						←	→											
Operational proof of complete combustor/HEX embodiment															←	—	—	→			

planned to check out the fundamental combustor operability aspect of the preliminary design, i.e., the maintenance of convection-type ceramic surface in a sufficiently clean condition under the various operating regimes of a cyclone combustor. This operability checkout can be conducted with present-day ceramics in existing steam boiler furnaces. During the five-year Phase II period the presently funded programs for development of NOX removal by catalytic combination with ammonia would be monitored, and if necessary augmented, so as to have a resolution by the close of Phase II. The metals development program would be conducted in the laboratory and in existing steam boilers in a manner similar to that described for the pulverized coal preliminary design of Section 3.1. Thus, at the close of Phase II, i.e., five years into the program, the technology would be available to design a significantly sized pilot installation. The pilot would be designed, fabricated, erected, and operated for several thousand hours during the seven-year period allocated to Phase III. Seven years are allocated to this effort because of the complexities of ceramic development and the size of the installation necessary for significant results.

The estimated $17 million cost of the five-year Phase II program is detailed in Section 3.4.2, which follows. These Phase II costs include about $2 million of metals and piping R&D which will be partially accomplished in the dry bottom P.C. furnace development outlined in Section 3.1. Confirmatory metals R&D will be necessary in the cyclone combustor environment, which differs from the P.C.

An overall estimate of the combined costs of Phases II and III is $45 million. This is based on the following assumptions:

1. The 2250 F program Phase II costs are reduced by $1 million by metals and piping development on preceding lower temperature programs.

2. A pilot installation of 35 MWe equivalent size is feasible for some useful purpose, perhaps cogeneration.
3. Design and fabrication of the combustor/HEX and its directly supporting auxiliaries are chargeable to the program.
4. All development activities related to the combustor/HEX are chargeable.
5. Design, installation and development of balance of plant equipment, including turbomachinery, is not chargeable.
6. Fuel and operating labor are not chargeable.

3.4.2 Phase II R&D Plan

An outline of the content, timing, and estimated costs of Phase II is presented in Table 3.4.4.

TABLE 3.4.4. PHASE II R&D PLAN - 2250 SLAGGING CYCLONE COMBUSTOR

R&D Activity	Years 1	2	3	4	5	K$
1. **Ceramics** - All aspects of design, fabrication and utilization						13,000
Technology review, coordinate with ongoing R&D	▭					
Development plans; basic materials; manufacture and Q.C.; characterization for strength, environmental compatibility; assembly and maintainability; code acceptance; design procedures	▭					
Manufacturing facilities acquisition	▭	▭	▭			
Test rig and test facilities and samples acquisition	▭	▭	▭	▭		
Experimentation Manufacture, assembly, mechanical operations, strength, temperature effects, physical characteristics, environmental efforts - existing cyclone boilers, working fluids	▭	▭	▭	▭	▭	
Results analysis	▭	▭	▭	▭	▭	
Define available properties				▭	▭	
Define design procedures				▭	▭	
2. **Metals - fireside corrosion**						1,000
Technology review, coordinate with ongoing R&D	▭					
Analysis and selection of candidate metals for test	▭					
Development plan, walls and convection tubes in existing cyclone combustor environments	▭					
Development plan, walls and convection tubes in modified fire side environments	▭					
Test rig and facility design and procurement	▭					
Testing in several boilers with several coals	▭	▭	▭	▭		
Supporting laboratory testing	▭	▭	▭	▭		
Results analysis			▭	▭		
Define acceptable metals for each environment and temperature zone			▭	▭		
3. **Metals - working fluids side corrosion**						125
Technology review, coordinate with ongoing R&D	▭					
Development plan, He/O$_2$, He/CO$_2$PO$_2$ mixtures	▭					
Sample and test fixture procurement	▭					
Laboratory testing - corrosion effects - confirm conductance	▭					
Results analysis	▭	▭				
Define acceptable metals/working fluids combinations		▭				
4. **Internally Insulated Piping**						750
Technology review, coordinate with ongoing R&D	▭					
Development plan	▭					
Hardware and test fixture design and procurement	▭					
Laboratory testing and development	▭	▭				
Results analysis - definition of adequate design		▭				
5. **Boiler and Pressure Vessel Code Acceptance - Ceramics**						250
Plan, consultant acquisition, ceramics manufacturer coordination, code committees contacts and coordination						
Code case preparations				▭	▭	
Code case submittals and pursuit					▭	
6. **Boiler and Pressure Vessel Code Acceptance - New Metals**						120
Plan, consultant acquisition, alloy manufacturer coordination	▭					
Code case preparations	▭					
Code case submittals and pursuit	▭	▭	▭			
7. **Cyclone Furnace Operations**						630
Prepare development plan	▭					
Identify and obtain cooperation re test boilers	▭					
Prepare sample heating surface	▭					
Conduct tests	▭					
Analyze results	▭	▭				
Define design procedures		▭				

TABLE 3.4.4. (CONT'D)

R&D Activity	Years 1	2	3	4	5	K$
8. <u>NOX Control</u>						100
Technology review, coordinate with ongoing R&D	▬	▬	▬	▬	▬	
Analyze results and assess position					▬	
9. <u>Analysis and Design Refinement</u>						1,000
Analyze to optimize rated operating requirements, working fluid composition, temperature, pressures	▬					
Analyze to optimize circuitry, surface arrangement, alloy applications, control capability, etc., resolve questions regarding relative expansions, thermal strains, low cycle fatigue, etc.	▬	▬	▬			
Prepare setting drawings			▬	▬		
10. <u>Prepare Phase III Program Plan</u>					▬	50
TOTAL						17,025

4.0 DISCUSSION OF RESULTS

The purpose of this section is to provide a general discussion of the results of the research and development planning, and to bring out the interrelationships among the development plans for the four preliminary designs.

The R&D plans presented in the body of this report are the result of a long chain of study events, i.e., the identification of promising CCGT cycles and working fluids, the evaluation of design criteria and candidate conceptual designs for the coal fired combustor/heat exchangers providing the heat input to the cycles, the preliminary design of the selected combustor/heat exchanger concepts, the identification of the key technical features of those preliminary designs which require R&D prior to the achievement of technology readiness for the overall combustor/heat exchanger design concept, and the planning of R&D programs appropriate for the resolution of the technology problems. The cycle work is presented in the Cycles and Working Fluids report, the design work is presented in the Design report, and the key features are identified and discussed in the Key Features report. Thus, the R&D plans presented in this report concern specific combustor/heat exchanger preliminary designs which service the needs of specific CCGT cycles. It is believed however that the preliminary designs deal with combustor/heat exchanger concepts that can be applied to service a broad range of cycle requirements, so that the designs and the R&D plans may be taken to deal with classes of combustor/heat exchangers whose applicability is much broader than to a single specific cycle arrangement and operating condition.

The periods projected for research and development from the close of the present Phase I study to the achievement of "technology readiness" vary from 8 to 12 years, depending principally upon the maximum CCGT working fluid operating temperature. It has been possible to devise an R&D plan for each preliminary design which involves an initial short and relatively inexpensive period of component and laboratory testing to verify the fundamental design principles of the preliminary design concept. This initial "Phase II" period is followed in each case by a longer and substantially more expensive Phase III period during which a significantly sized combustor/heat exchanger module embodying the fundamental design concepts is designed, fabricated, and operated for a sufficient period to supply operational proof of the underlying concepts.

An examination of the R&D plans shows that the major costs during the Phase II period are required for research in the area of materials of construction. All of the designs involve the application of metals at elevated temperatures in fireside enivronments that require extensive research. Relatively little fundamental research on metal materials has been planned, i.e., formulation, manufacturing techniques, and fabrication. With the ceramic materials of construction needed for application at CCGT working fluid temperatures higher than 1550 F, the R&D plans involve all areas of development, i.e., formulation, manufacture, quality control, assembly, strength properties, design procedures, fire side and working fluid side corrosion effects, etc. The expense and time period required for ceramics development is substantially greater than that required for metals, and the outcome less certain.

Each of the preliminary designs represents an extension of steam boiler combustor/heat exchanger technology, and the R&D effort planned for combustor/heat exchanger functional performance development is relatively modest. In the case of the two preliminary designs which rely upon atmospheric fluidized bed combustion, the Phase II effort planned in the area of development of fluidized bed combustion and heat transfer technology is based upon the assumption that research in these areas to support steam boiler development will continue at a substantial level. The fluidized bed technology development planned for CCGT support covers only those special areas unique to the CCGT application and relies upon steam boiler fluidized bed technology support for application in all common areas.

Each R&D plan provides for additional analysis and design refinement during the Phase II activities so as to prepare for the design and fabrication of the test module that will be operated during Phase III. The "setting drawings" would be prepared for a full-size, (presumably 350 MWe), embodiment of the design concept. The setting drawings constitute a much more detailed design layout than the preliminary design drawings made during this study effort, and thus require the resolution of many of the design questions that will inevitably arise. The effort provides better preparation for the design and fabrication to be undertaken in Phase III.

There is much room for difference of opinion as to the order in which to undertake the R&D programs. The funding requirements for the Phase II portions of each program are modest, and the programs are structured so that their Phase II efforts could be undertaken concurrently. The ideal plan would be to undertake all four programs. This would provide the greatest depth for CCGT combustor/heat exchanger development. If development funds are limited it is recommended that the Phase II efforts on the dry bottom pulverized coal and fluidized bed combustor/heat exchangers for the 1550 F (and lower) CCGT working fluid temperatures be undertaken concurrently. At the same time, a beginning ceramics development program should be undertaken, which would result in a longer term ceramics development than visualized in these R&D plans, but avoid a very large time gap between the achievement of the 1550 F working fluid temperature capabilities and the 1750 F and higher capabilities.

The arguments for concurrent development of the two 1550 F combustor/heat exchanger concepts, plus a start on ceramics development, include the following.

1. The pulverized coal technology is best known and most likely to succeed.

2. The fluidized bed technology however promises substantial improvement in the costs of sulphur oxides emissions control and may also be less costly in its alloy requirements. It does not appear reasonable to ignore fluidized bed technology when steam boiler fluidized bed developments may tend to obsolete pulverized coal.

3. Neither does it appear reasonable to place the entire reliance for CCGT combustor/heat exchangers upon fluidized bed technology when continued research in fluidized beds for steam boilers may uncover problems that prevent its application for power generation purposes.

4. The metals technology required for the 1550 F CCGT working fluid temperatures is also essential to the 1750 F and higher applications. It will not go to waste if the ultimate applications are at 1750 F or higher.

5. Usable ceramics promise significant efficiency improvement. Their development should not be held completely in abeyance until 1550 F capabilities are in hand.

The diverse nature of the planned R&D efforts argue for the undertaking of the programs by teams of contractors, similar in some respects to the Rockwell/Battelle/R.M. Parsons/GE team that conducted this study. The make-up of the teams would include equipment manufacturers, such as Rockwell; materials research organizations, such as Battelle Laboratories; metals manufacturers; ceramics manufacturers; one or more public utilities with existing installations suitable for experimentation; and an A&E outfit for overall power plant considerations.

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