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Concept for a Super-Clean Super-Efficient Pressurized Fluidized-Bed Combustion System

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ABSTRACT

A paper study for a highly efficient, environmentally benign, coal-fired electric power generation system, is presented. This system falls in the category of pressurized fluidized-bed combustion (PFBC) systems which has been dubbed super-clean super-efficient PFBC's. The system presented starts with the second-generation PFBC concept and adds an advanced gas turbine, a solid oxide fuel cell, a supercritical steam cycle, a second low-temperature rankine cycle which pulls energy from the steam condenser, and inlet air cooling. The thermodynamic efficiency of the system is calculated to be 61.8 percent based on the higher heating value (HHV).

INTRODUCTION

The Department of Energy (DOE) has been promoting the development of Pressurized Fluidized-Bed Combustors (PFBCs) for over 2 decades. The technology has evolved from first- to second-generation systems (see figure 1) with significant improvements in system efficiency, emissions, and cost of energy. Pressures from competing technologies such as Integrated Gasification Combined Cycle (IGCC) (45 - 52 percent thermal efficiency), natural gas combined cycle (60+ percent thermal efficiency), indirect fired cycle systems (50 - 60+ percent thermal efficiency), as well as increasingly stringent environmental regulations (predicted to be as low as 1/10 current New Source Performance Standards by 2010), continue to drive PFBC systems to higher efficiencies, lower costs of energy, and lower environmental impact. To meet these challenges, paper studies which explore more efficient and environmentally more benign PFBC systems have been initiated. These advanced systems have been dubbed super-clean super-efficient PFBC (SPFBC) and are required to have efficiencies >50 percent with sulfur and NO_x emissions ≤1/10 the current New Source Performance Standards (NSPS).

In order for PFBC systems to remain competitive, a super-clean super-efficient system must be ready for commercial demonstration in the 2005 time frame. Figure 2 shows the projected PFBC development cycle. To meet this schedule, the SPFBC must rely on technologies which are at least at a sub-scale component test level of development.

In an effort to identify the performance envelope for an SPFBC system, this first study is primarily aimed at maximizing cycle efficiency. Though capital costs are by no means neglected in the study, they do not play as prominent a role as may be required later in the development cycle. Bear in mind that it is possible that none of the concepts presented in this initial SPFBC system will ultimately be adopted. The primary goal of this first study is to generate a performance benchmark by which to measure other concepts.

BACKGROUND

Before beginning the presentation of the SPFBC, some background regarding the evolution of the PFBC concept is appropriate. From its inception, the PFBC has been built to take advantage of the excellent solid to gas contact and high heat transfer rates that characterize this technology. Figure 1 shows how the PFBC technology has evolved over the past 2 decades.

The basic- or first-generation PFBC is shown inside the gray shaded area of Figure 1. The fluid-bed, which may be either bubbling or circulating, generates steam for an industrial process or power generation. The 1600°F, high-pressure exhaust gas is expanded in a gas turbine which in turn drives both a generator for additional electric power and an air compressor to pressurize the fluid-bed. This first-generation system offers a more efficient, environmentally benign, and lower cost alternative to conventional pulverized-coal boilers. About a dozen first-generation PFBC demonstration plants have been built over the last decade. Figure 3 shows the status of both the first- and second-generation PFBC projects world-wide. Commercial scale (> 60 megawatts {MW} electric) first-generation PFBC demonstration plants have accumulated over 40,000 hours of operation.

The thermal efficiency of the first-generation system could be increased from around 40 percent to 45+ percent by increasing the gas temperature to the expansion turbine. In the advanced- or second-generation PFBC this is accomplished by adding the partial gasifier (referred to as a carbonizer) and a topping combustor to the first-generation system. The second-generation PFBC is shown graphically within the dashed lines of Figure 1. In the second-generation PFBC, the fuel gas from the carbonizer is mixed with the oxygen-rich exhaust from the PFB in the topping combustor. The resultant exit gases from the topping combustor are hot enough to power an efficient state-of-the-art gas turbine. In most second-generation systems, the gas turbine accounts for approximately half of the plants power generation capability. The second-generation PFBC is in the sub-scale component integration portion of the development cycle. The first commercial demonstration plants are scheduled for later in the decade.

Though not shown in Figure 1, there is another way to achieve the efficiency gains of the second-generation system without adding the complexity and expense of a carbonizer. This system has been referred to as a 1 1/2-generation PFBC and uses natural gas or some other fuel in place of carbonizer gas to increase the PFB exhaust gas temperature in the topping combustor. The 1 1/2-generation concept offers first-generation PFBC systems a low capital cost path to increase power production and plant efficiency.

DESCRIPTION OF SUPER-CLEAN SUPER-EFFICIENT PFBC

The super-clean super-efficient PFBC (SPFBC) concept is a high-efficiency, low-emissions coal-fired power generation system. The concept is based on the second-generation PFBC system and uses technologies which are either commercially available or in development at the pilot scale. The effort to conceptualize this first SPFBC system has three goals. First, establish realistic performance targets; second, determine which technologies are critical to a super-clean super-efficient system; and third, identify components and/or concepts which may be advantageously applied to current first- and second-generation PFBC systems to improve their performance.

Figure 2 shows the current projected development cycle for all of the PFBC systems. As indicated, the SPFBC is just entering its initial development phase. There are currently no funds earmarked specifically for development of the SPFBC concept though internal preliminary paper studies, such as the one presented here, are proceeding.

System Description

The SPFBC includes all of the components shown within the solid line in Figure 1. To improve the thermodynamic efficiency of the carbonizer/gas turbine section of the cycle (referred to as the topping cycle) of the second-generation PFBC system, a pressurized solid oxide fuel cell (SOFC) is added. SOFC's are relatively tolerant, at least in fuel cells terms, to sulfur compounds. In addition, once contaminated with sulfur they seem to be regenerable. Though a sulfur absorbing guard bed (e.g. zinc-oxide) is required to protect the SOFC, its tolerance makes it more forgiving of accidental poisoning by sulfur.

Because the SOFC operating temperature is about 1800°F, it has a high temperature waste heat stream. The SPFBC uses the SOFC's waste heat to preheat the carbonizer combustion air. Since the carbonizer no longer needs extra air to burn coal to heat the incoming air, the air throughput decreases and the chemical energy content in the carbonizer gas increases.

SOFC's are generally designed to burn 85 percent of the chemical energy in their inlet fuel stream during the galvanic reactions. In the SPFBC, the low energy (around 15 to 30 BTU/standard cubic foot) fuel gas exiting the fuel cell is mixed with fresh carbonizer gas and the oxygen-rich PFB exhaust gas in the topping combustor. The topping combustor used in the SPFBC is designed to convert much of the NO_x and fuel-bound nitrogen in the PFB and carbonizer exit gas streams into N_2. This is achieved by balancing the excess air in the PFB with the quantity of available fuel gas such that the stoichiometry of the mixture will be between 1.1 and 1.6 fuel rich in the first stage of the topping combustor. The fuel is then burned to completion in the fuel lean second stage of the combustor using a mixture of the spent fuel cell oxidizer and fresh compressor air.

In the bottom left corner of Figure 1, a second low-temperature bottoming cycle is added to produce additional power by extracting energy from the steam condenser, the flue gas, and the gas turbine air cooler. In the SPFBC this second bottoming cycle is modelled as a rankine cycle using ammonia as a working fluid. This type of equipment is common to the geothermal power production industry. The efficiency of this low-temperature bottoming cycle will be optimized in future studies by replacing the ammonia working fluid with a hydrocarbon or mixture of hydrocarbons.

Finally, an inlet air chiller is added to reduce the size and energy requirements of the system air compressor. The inlet air is cooled to around 40°F, which is warm enough to allay the compressor manufacturers' concerns about ice formation. The use of an air dryer would allow for lower inlet air temperatures which would further decrease the energy consumption of the air compressor. Based on some simple thermodynamic calculations, it appears that the incremental energy needed to drive the chiller becomes equal to the incremental energy saved in the air compressor at a temperature near -20°F. However, the actual air cooling temperature will probably need to be higher than this to account for energy costs associated with the air drying.

In addition to the preceding new components, the SPFBC also uses an advanced 4500 pounds per square inch (psi) 1100°F/1075°F/1050°F steam cycle, and an advanced 2450 inlet temperature gas turbine with a 14:1 pressure ratio.

Thermodynamic Performance

Table 1 gives the thermodynamic performance of several configurations of PFBC's. The values are calculated using the public version of the Advanced System for Process Engineering (ASPEN™) software. As of this writing, the SPFBC simulation has not been optimized but the values are not expected to change significantly.

The first column of Table 1 shows the ASPEN™ predictions for the performance of the current concept second-generation PFBC. This second-generation PFBC simulation acts as a baseline for judging the relative importance of each of the SPFBC modifications. The top half of Table 1 gives the power output in MW for each of the system components. Negative numbers indicate energy consumption. The net power produced by the baseline configuration is about 270 MW. The lower half of Table 1 gives the inlet temperature (T) in °F and the system pressure (P) in psi for the gas turbine and steam turbine respectively. The 2400 psi steam cycle operates at 1000°F with a 1000°F reheat, while the 4500 psi cycle operates at 1100°F with a 1075°F and 1050°F reheat. Finally, the bottom of Table 1 indicates if the ammonia turbine, fuel cell, and inlet air chiller are included (Y) in the simulation or not (N).

In columns 2 through 7 of Table 1, the effects of each of the SPFBC components on the system efficiency are examined. The synergistic effects are somewhat discounted by this type of analysis, but it is still useful for gauging the relative importance of the subsystems. A comparison of columns 1, 2, 3, and 4 indicates that the advanced steam cycle, with its 5.6 point efficiency gain, is more than three times as important to the SPFBC system thermodynamic efficiency as is the higher temperature gas turbine[1]. Further, an examination of columns 5 through 7 illustrates that both the second low-temperature bottoming cycle and the fuel cell/carbonizer preheat systems add about 3.3 and 3.8 points respectively to the system efficiency. In contrast, the inlet air chiller only adds 1 MW to the SPFBC output. Adding all of the SPFBC components including the advanced gas turbine and steam cycle results in a thermodynamic efficiency for the SPFBC of 61.8 percent.

Environmental Performance

The most desirable method of improving environmental performance is to increase the system energy conversion efficiency and burn less fuel. With a thermal efficiency near 62 percent, the SPFBC is projected to produce 40 percent less CO_2 than a conventional pulverized-coal plant with a nominal 35 percent thermal efficiency. The SPFBC will also require 40 percent less coal, produce 40 percent less solid waste, dump 40 percent less thermal energy into the environment, and be significantly smaller than its conventionally fired, pulverized-coal counterpart.

The SPFBC low NO_x topping combustor, which is very similar to current second-generation PFBC topping combustor hardware, is expected to reduce NO_x emissions below the current achievable levels of 40 to 140 parts per million (ppm). It is widely accepted [1,2,3], based on experiments and chemical equilibrium codes, that given the appropriate fuel-rich stoichiometry, temperature, and residence time, a significant portion of the NO_x, in a gas stream will convert to N_2. In the SPFBC topping combustor, all of the PFB exhaust gas passes through the fuel-rich zone of the combustor. The result is that NO_x, which has already been formed in the PFB, can be converted to N_2. Chemical equilibrium calculations indicate that NO_x emissions could be

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[1]Using an advanced aeroderivative gas turbine with a 30:1 pressure ratio and higher firing temperature may increase the gas turbine contribution to the SPFBC efficiency. The effect of a 30 atmosphere system pressure on the performance and cost of the SPFBC is being investigated.

reduced to ≈10ppm. More detailed performance predictions using chemical kinetics models are currently underway. However, given the current state-of-the-art in kinetics modeling, physical testing and measurements are also needed.

The SPFBC uses all of the SO_x and alkali capture technology currently planned for the second-generation PFBC. SO_x removal is expected to be 98-99 percent which translates to emissions of 4-5 tons/MW-yr for high sulfur bituminous coal (3 percent sulfur). The turbine criterion of 20 - 50 parts per billion alkali can be achieved using a sorbent such as emathlite. Several alkali removal configurations are being considered, including injection of alkali sorbent in the particulate filter vessel.

DISCUSSION OF FINDINGS

As with any paper study, the SPFBC efficiencies reported in the previous section should be taken with a healthy amount of skepticism. At this stage, these simulations should be viewed as giving ballpark performance information and as providing insight about the relative importance of the various subsystems that make up the SPFBC. With this in mind, the following preliminary assessment of the system can be made.

The simulations indicate the most significant improvement in cycle efficiency (5.6 point gain) results from the advanced 4500psi/1100°F/1075°F/1050°F steam cycle. These supercritical steam conditions are considered state-of-the-art [4] with systems at similar conditions being operated in Japan [5]. In addition, more advanced 5000psi/1200°F/1150°F/1150°F cycles are expected to be available in the near-term.

At a 1.7 point SPFBC system efficiency gain, the high-temperature gas turbine appears to have a smaller impact on system efficiency than might be expected. The 2450°F inlet temperature advanced turbine has a simple cycle efficiency which is about 3 points better than the base 2300°F turbine. By comparison, replacing the sub critical 2400 psi steam cycle with the supercritical 4500 psi cycle results in a 13 point increase in the steam cycle efficiency. In addition, increases in the steam cycle efficiency have more effect on system efficiency than do increases in the gas turbine efficiency. Unlike coal gasification systems where most of the thermal energy of the coal is used by the gas turbine, in PFBC systems about 40 percent of the energy in the coal is routed directly to the steam cycle and never sees the gas turbine. Since the gas turbine also dumps its waste heat to the steam cycle, the steam cycle receives about 75 percent of the thermal energy from the coal. By contrast, the gas turbine only sees about 60 percent of the energy. For this reason, improvements in the efficiency of the gas turbine do not have as great an impact on the SPFBC performance as do steam cycle improvements.

The low-temperature second bottoming cycle and the solid oxide fuel cell each have a moderate impact on the SPFBC efficiency with improvements of 3.3 and 3.7 points respectively. The low temperature bottoming cycle is a commercially available system which is used extensively in the geothermal energy market. These types of systems have simple cycle efficiencies in the 10 percent to 15 percent range and cost on the order of $1000/KW (not including balance of plant equipment). As a retrofit, this second bottoming cycle may prove to be an economical and environmentally benign method of increasing power and decreasing thermal discharge from existing power plants. The pressurized solid oxide fuels are not quite as mature and will require another 5 to 10 years to reach a similar level of development.

Finally, using a chiller to cool the inlet air does decrease the amount of energy required by the inlet air compressor. This translates into a 7 percent increase in the gas turbine output. However, the air cooling also produced a 5 percent decrease in power from the steam cycle which, when coupled with the parasitic energy requirements of the chiller, results in a performance improvement of only 0.2 points in the SPFBC. Despite this less than stellar result, coupling an air dryer to the chiller and cooling the inlet air to sub-freezing temperatures (with creative heat recuperation) may prove to be a thermodynamic winner in gasification systems where the impact on the steam cycle will not be as severe.

Environmental Performance

The projected sulfur capture efficiency for advanced PFBC systems is about 98 to 99 percent. At 99 percent sulfur capture the SPFBC will meet the 1/10 NSPS sulfur emission goal. To meet the NO_x target of .05 pounds per million BTU (lbs/MMBTU) the SPFBC topping combustor will have to achieve NO_x emissions on the order of 20 parts per million by weight. This is about twice the theoretical minimum calculated using equilibrium chemistry models and about half what full scale tests of the state-of-the-art second-generation PFBC topping combustor are producing. If environmental regulations become more stringent there is always the less palatable option of down stream flue gas cleanup using proven sulfur and NO_x abatement systems.

CONCLUSIONS

The initial design of an SPFBC is presented along with a first-cut thermodynamic analysis. This paper study indicates that significant improvements in thermodynamic performance, beyond those currently projected for the second-generation PFBC concept, are possible. The second low-temperature bottoming cycle used in the SPFBC is commercially available and the supercritical steam cycle is expected to come down to a commercially attractive cost in the near future. Coupling these two systems with current second-generation PFBC systems would result in thermodynamic efficiencies in the mid-50 percent. Additional efficiency gains are possible by adding a fuel cell as an energy source and cabonizer air preheater. However, the proposed pressurized solid oxide fuel cell will not be ready for commercial scale demonstration for another 5 to 10 years. Increasing the firing temperature of the gas turbine while maintaining a 14:1 pressure ratio, results in a modest 2 point efficiency gain for the SPFBC system. However, increasing the pressure of the SPFBC, which will allow the use of high-pressure ratio aeroderivative turbine, may provide a more significant gas turbine contribution to the overall system efficiency. Finally, though compressor inlet air cooling has been shown to increase simple cycle gas turbine power output, it does not significantly increase system efficiency in a PFBC configuration. With a judicious use of regeneration, inlet air cooling may prove beneficial to gasification systems where 70 percent of the energy is generated by the gas turbine.

The SPFBC is expected to be able to meet the 1/10 NSPS for SO_x and NO_x without the need for flue gas cleanup. With the exception of the NO_x, all of the improvements in the environmental performance are part of the current second-generation PFBC program.

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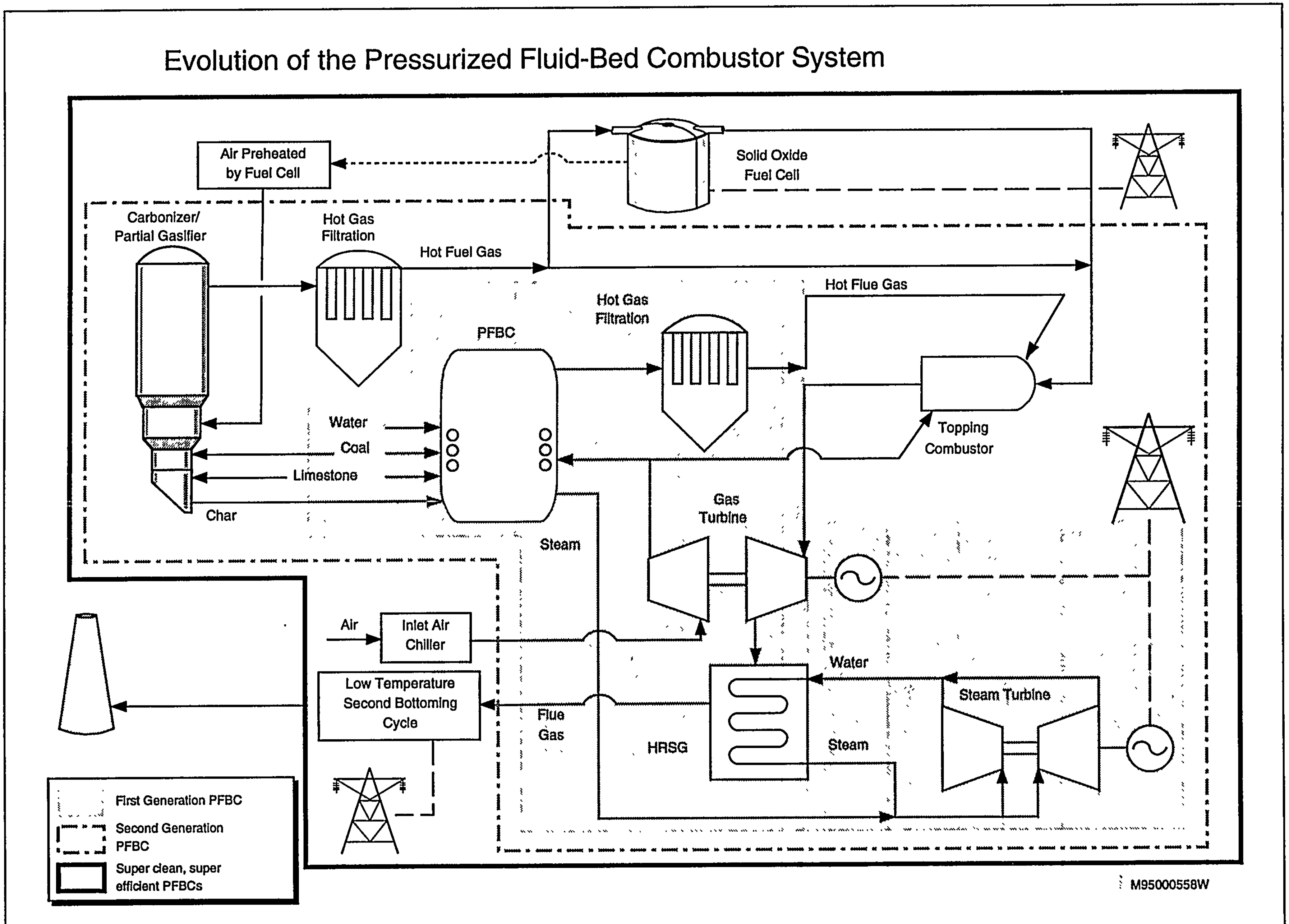

Figure 1 Evolution of the Pressurized Fluid-Bed Combustor System

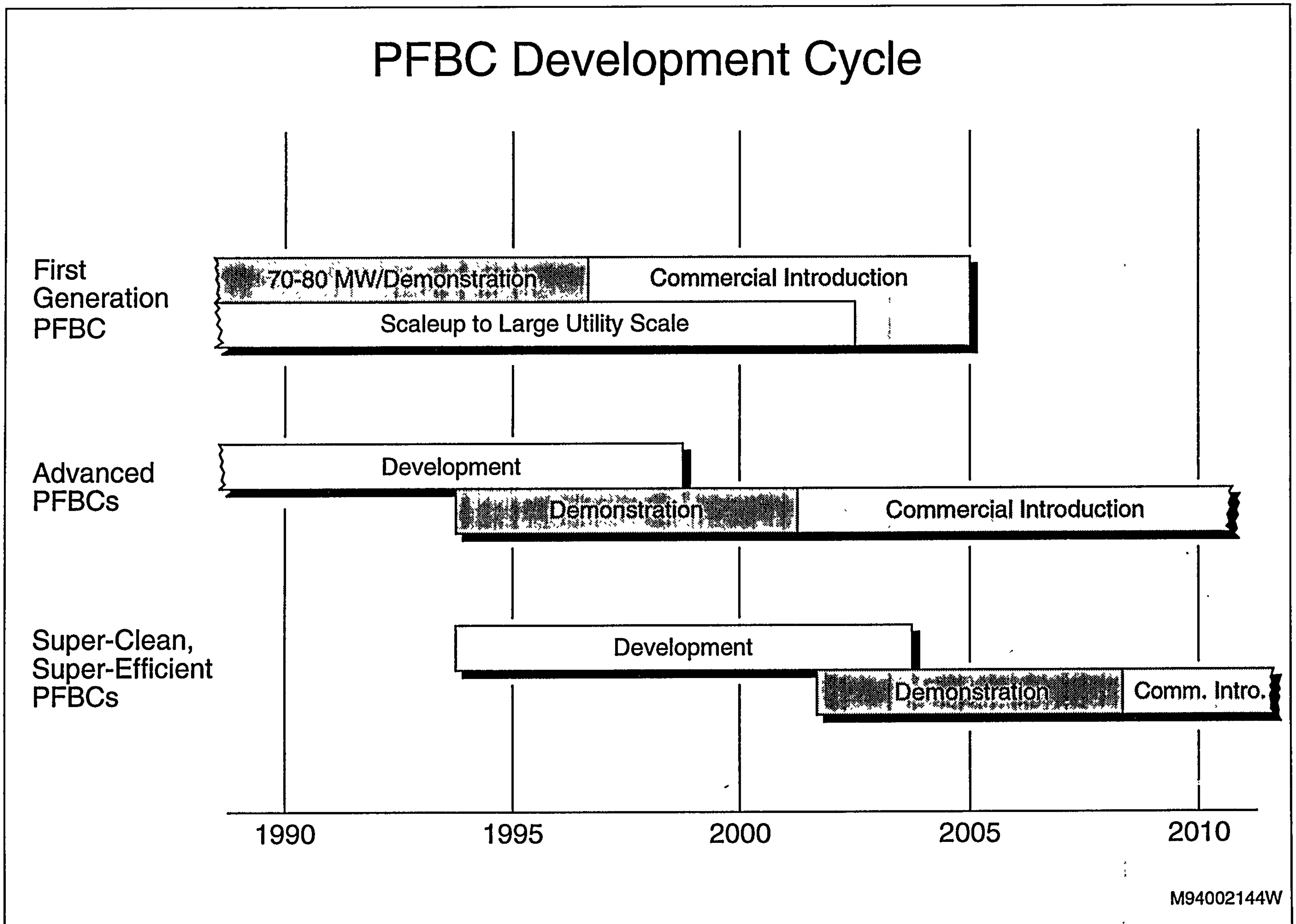

Figure 2 Current Development Schedule for the Pressurize Fluid-Bed Program

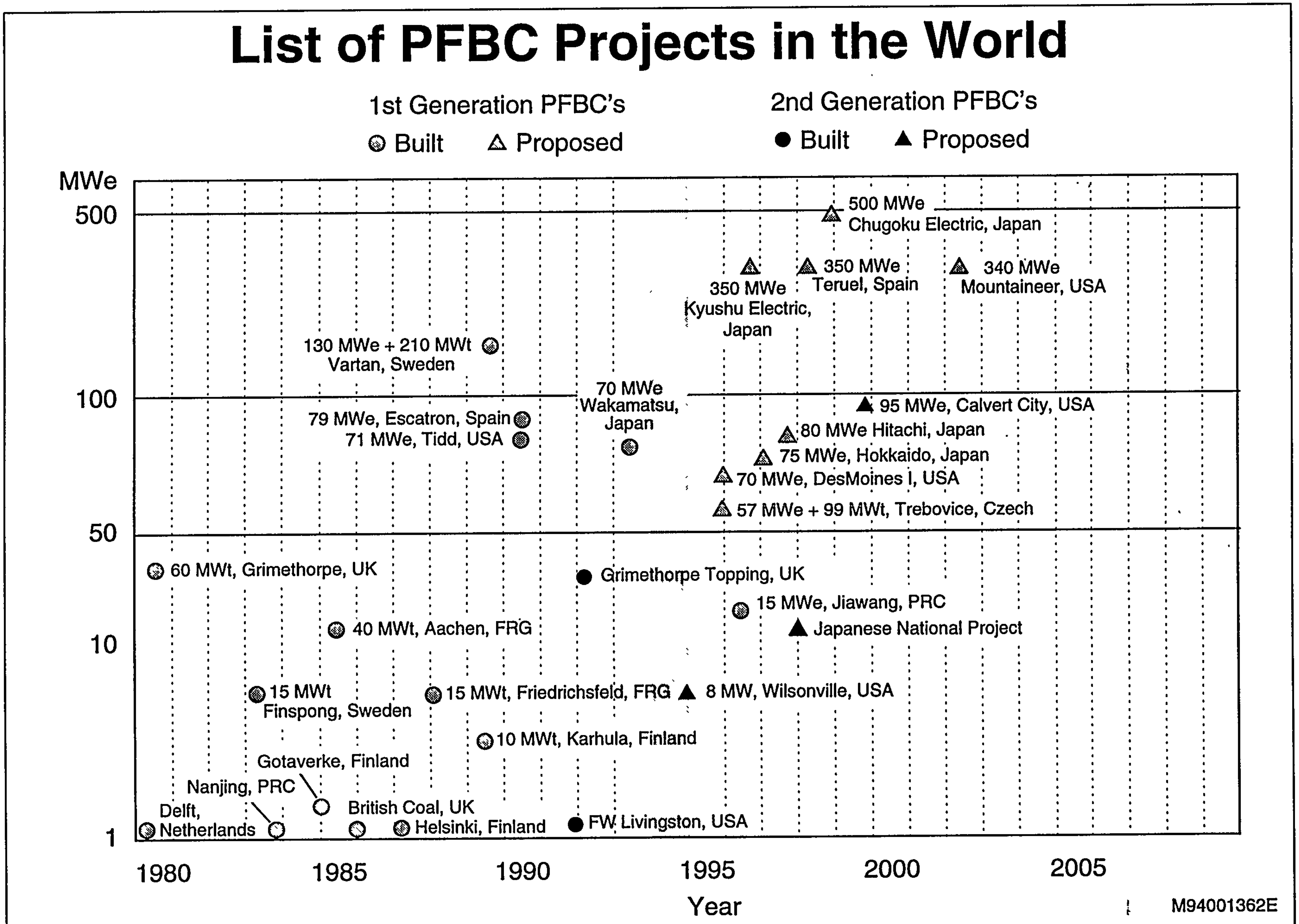

Figure 3 Pressurized Fluid-Bed Combustion Systems Built or Planned World Wide Displayed by System Type, Generation Capacity, and Year of Operation.

	Second Gen. PFBC	PFBC with adv. Gas T.	PFBC with adv. Steam T.	PFBC with adv. GT & ST	PFBC with 2nd B.C.	PFBC with B.C. & Chiller	PFBC with B.C., F.C., Chiller	Complete SPFBC
Gas Turbine (MW)	139.4	156	139.5	155.5	139.4	148.6	156.5	141.3
Steam Turbine	138.3	131.4	173.4	165	138.3	132.2	98.4	185
Second Bottoming Cycle	0	0	0	0	19.4	18.6	17.5	18.9
Fuel Cell System	0	0	0	0	0	0	48.3	26.9
Inlet Air Chiller	0	0	0	0	0	-1.5	-1.7	-1.2
Misc.	-3.5	-3.4	-5.9	-5.6	-3.5	-3.3	-2.7	-6.6
Auxiliary	-5	-5.2	-5.6	-5.8	-5.4	-5.4	-5.4	-6.6
Total Megawatts	269.3	278.9	301.3	309.1	288.3	289.1	310.9	357.8
Efficiency (HHV %)	46.5	48.2	52.1	53.4	49.8	50	53.7	61.8
Gas Turbine (T)	2300	2450	2300	2450	2300	2300	2300	2450
Steam Turbine (P)	2400	2400	4500	4500	2400	2400	2400	4500
Second Bottoming Cycle	N	N	N	N	Y	Y	Y	Y
Fuel Cell System	N	N	N	N	N	N	Y	Y
Inlet Air Chiller	N	N	N	N	N	Y	Y	Y

Table 1 Pressurized Fluid-Bed Combustion System Simulations Establish the Effect of Each of the Proposed Super-Clean Super-Efficient PFBC Sub-Systems.

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Thermodynamic Performance

Table 1 gives the thermodynamic performance of several configurations of PFBC's. The values are calculated using the public version of the Advanced System for Process Engineering (ASPEN™) software. As of this writing, the SPFBC simulation has not been optimized but the values are not expected to change significantly.

The first column of Table 1 shows the ASPEN™ predictions for the performance of the current concept second-generation PFBC. This second-generation PFBC simulation acts as a baseline for judging the relative importance of each of the SPFBC modifications. The top half of Table 1 gives the power output in MW for each of the system components. Negative numbers indicate energy consumption. The net power produced by the baseline configuration is about 270 MW. The lower half of Table 1 gives the inlet temperature (T) in °F and the system pressure (P) in psi for the gas turbine and steam turbine respectively. The 2400 psi steam cycle operates at 1000°F with a 1000°F reheat, while the 4500 psi cycle operates at 1100°F with a 1075°F and 1050°F reheat. Finally, the bottom of Table 1 indicates if the ammonia turbine, fuel cell, and inlet air chiller are included (Y) in the simulation or not (N).

In columns 2 through 7 of Table 1, the effects of each of the SPFBC components on the system efficiency are examined. The synergistic effects are somewhat discounted by this type of analysis, but it is still useful for gauging the relative importance of the subsystems. A comparison of columns 1, 2, 3, and 4 indicates that the advanced steam cycle, with its 5.6 point efficiency gain, is more than three times as important to the SPFBC system thermodynamic efficiency as is the higher temperature gas turbine[1]. Further, an examination of columns 5 through 7 illustrates that both the second low-temperature bottoming cycle and the fuel cell/carbonizer preheat systems add about 3.3 and 3.8 points respectively to the system efficiency. In contrast, the inlet air chiller only adds 1 MW to the SPFBC output. Adding all of the SPFBC components including the advanced gas turbine and steam cycle results in a thermodynamic efficiency for the SPFBC of 61.8 percent.

Environmental Performance

The most desirable method of improving environmental performance is to increase the system energy conversion efficiency and burn less fuel. With a thermal efficiency near 62 percent, the SPFBC is projected to produce 40 percent less CO_2 than a conventional pulverized-coal plant with a nominal 35 percent thermal efficiency. The SPFBC will also require 40 percent less coal, produce 40 percent less solid waste, dump 40 percent less thermal energy into the environment, and be significantly smaller than its conventionally fired, pulverized-coal counterpart.

The SPFBC low NO_x topping combustor, which is very similar to current second-generation PFBC topping combustor hardware, is expected to reduce NO_x emissions below the current achievable levels of 40 to 140 parts per million (ppm). It is widely accepted [1,2,3], based on experiments and chemical equilibrium codes, that given the appropriate fuel-rich stoichiometry, temperature, and residence time, a significant portion of the NO_x, in a gas stream will convert to N_2. In the SPFBC topping combustor, all of the PFB exhaust gas passes through the fuel-rich zone of the combustor. The result is that NO_x, which has already been formed in the PFB, can be converted to N_2. Chemical equilibrium calculations indicate that NO_x emissions could be

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[1]Using an advanced aeroderivative gas turbine with a 30:1 pressure ratio and higher firing temperature may increase the gas turbine contribution to the SPFBC efficiency. The effect of a 30 atmosphere system pressure on the performance and cost of the SPFBC is being investigated.

reduced to ≈10ppm. More detailed performance predictions using chemical kinetics models are currently underway. However, given the current state-of-the-art in kinetics modeling, physical testing and measurements are also needed.

The SPFBC uses all of the SO_x and alkali capture technology currently planned for the second-generation PFBC. SO_x removal is expected to be 98-99 percent which translates to emissions of 4-5 tons/MW-yr for high sulfur bituminous coal (3 percent sulfur). The turbine criterion of 20 - 50 parts per billion alkali can be achieved using a sorbent such as emathlite. Several alkali removal configurations are being considered, including injection of alkali sorbent in the particulate filter vessel.

DISCUSSION OF FINDINGS

As with any paper study, the SPFBC efficiencies reported in the previous section should be taken with a healthy amount of skepticism. At this stage, these simulations should be viewed as giving ballpark performance information and as providing insight about the relative importance of the various subsystems that make up the SPFBC. With this in mind, the following preliminary assessment of the system can be made.

The simulations indicate the most significant improvement in cycle efficiency (5.6 point gain) results from the advanced 4500psi/1100°F/1075°F/1050°F steam cycle. These supercritical steam conditions are considered state-of-the-art [4] with systems at similar conditions being operated in Japan [5]. In addition, more advanced 5000psi/1200°F/1150°F/1150°F cycles are expected to be available in the near-term.

At a 1.7 point SPFBC system efficiency gain, the high-temperature gas turbine appears to have a smaller impact on system efficiency than might be expected. The 2450°F inlet temperature advanced turbine has a simple cycle efficiency which is about 3 points better than the base 2300°F turbine. By comparison, replacing the sub critical 2400 psi steam cycle with the supercritical 4500 psi cycle results in a 13 point increase in the steam cycle efficiency. In addition, increases in the steam cycle efficiency have more effect on system efficiency than do increases in the gas turbine efficiency. Unlike coal gasification systems where most of the thermal energy of the coal is used by the gas turbine, in PFBC systems about 40 percent of the energy in the coal is routed directly to the steam cycle and never sees the gas turbine. Since the gas turbine also dumps its waste heat to the steam cycle, the steam cycle receives about 75 percent of the thermal energy from the coal. By contrast, the gas turbine only sees about 60 percent of the energy. For this reason, improvements in the efficiency of the gas turbine do not have as great an impact on the SPFBC performance as do steam cycle improvements.

The low-temperature second bottoming cycle and the solid oxide fuel cell each have a moderate impact on the SPFBC efficiency with improvements of 3.3 and 3.7 points respectively. The low temperature bottoming cycle is a commercially available system which is used extensively in the geothermal energy market. These types of systems have simple cycle efficiencies in the 10 percent to 15 percent range and cost on the order of $1000/KW (not including balance of plant equipment). As a retrofit, this second bottoming cycle may prove to be an economical and environmentally benign method of increasing power and decreasing thermal discharge from existing power plants. The pressurized solid oxide fuels are not quite as mature and will require another 5 to 10 years to reach a similar level of development.

Finally, using a chiller to cool the inlet air does decrease the amount of energy required by the inlet air compressor. This translates into a 7 percent increase in the gas turbine output. However, the air cooling also produced a 5 percent decrease in power from the steam cycle which, when coupled with the parasitic energy requirements of the chiller, results in a performance improvement of only 0.2 points in the SPFBC. Despite this less than stellar result, coupling an air dryer to the chiller and cooling the inlet air to sub-freezing temperatures (with creative heat recuperation) may prove to be a thermodynamic winner in gasification systems where the impact on the steam cycle will not be as severe.

Environmental Performance

The projected sulfur capture efficiency for advanced PFBC systems is about 98 to 99 percent. At 99 percent sulfur capture the SPFBC will meet the 1/10 NSPS sulfur emission goal. To meet the NO_x target of .05 pounds per million BTU (lbs/MMBTU) the SPFBC topping combustor will have to achieve NO_x emissions on the order of 20 parts per million by weight. This is about twice the theoretical minimum calculated using equilibrium chemistry models and about half what full scale tests of the state-of-the-art second-generation PFBC topping combustor are producing. If environmental regulations become more stringent there is always the less palatable option of down stream flue gas cleanup using proven sulfur and NO_x abatement systems.

CONCLUSIONS

The initial design of an SPFBC is presented along with a first-cut thermodynamic analysis. This paper study indicates that significant improvements in thermodynamic performance, beyond those currently projected for the second-generation PFBC concept, are possible. The second low-temperature bottoming cycle used in the SPFBC is commercially available and the supercritical steam cycle is expected to come down to a commercially attractive cost in the near future. Coupling these two systems with current second-generation PFBC systems would result in thermodynamic efficiencies in the mid-50 percent. Additional efficiency gains are possible by adding a fuel cell as an energy source and cabonizer air preheater. However, the proposed pressurized solid oxide fuel cell will not be ready for commercial scale demonstration for another 5 to 10 years. Increasing the firing temperature of the gas turbine while maintaining a 14:1 pressure ratio, results in a modest 2 point efficiency gain for the SPFBC system. However, increasing the pressure of the SPFBC, which will allow the use of high-pressure ratio aeroderivative turbine, may provide a more significant gas turbine contribution to the overall system efficiency. Finally, though compressor inlet air cooling has been shown to increase simple cycle gas turbine power output, it does not significantly increase system efficiency in a PFBC configuration. With a judicious use of regeneration, inlet air cooling may prove beneficial to gasification systems where 70 percent of the energy is generated by the gas turbine.

The SPFBC is expected to be able to meet the 1/10 NSPS for SO_x and NO_x without the need for flue gas cleanup. With the exception of the NO_x, all of the improvements in the environmental performance are part of the current second-generation PFBC program.

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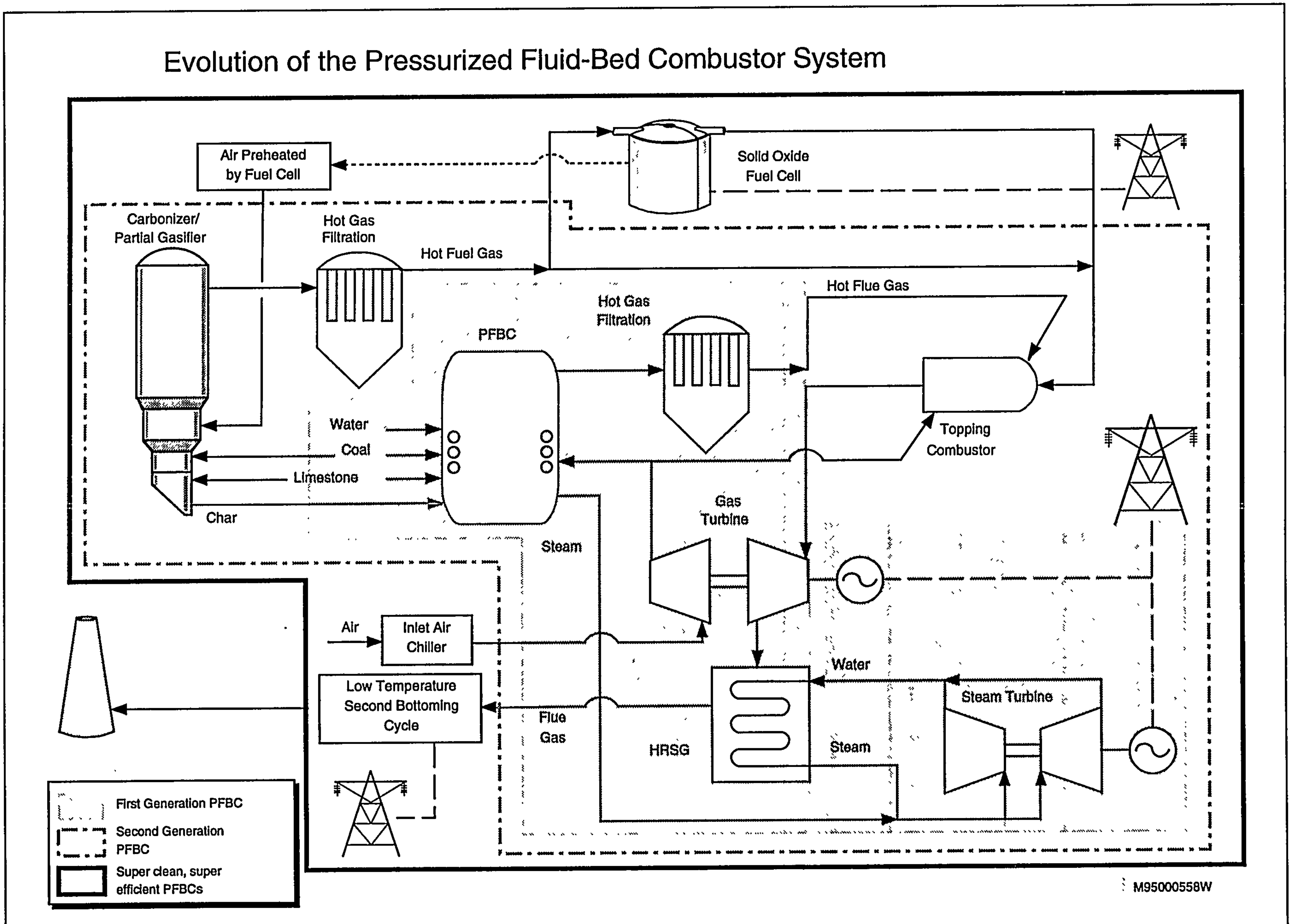

Figure 1 Evolution of the Pressurized Fluid-Bed Combustor System

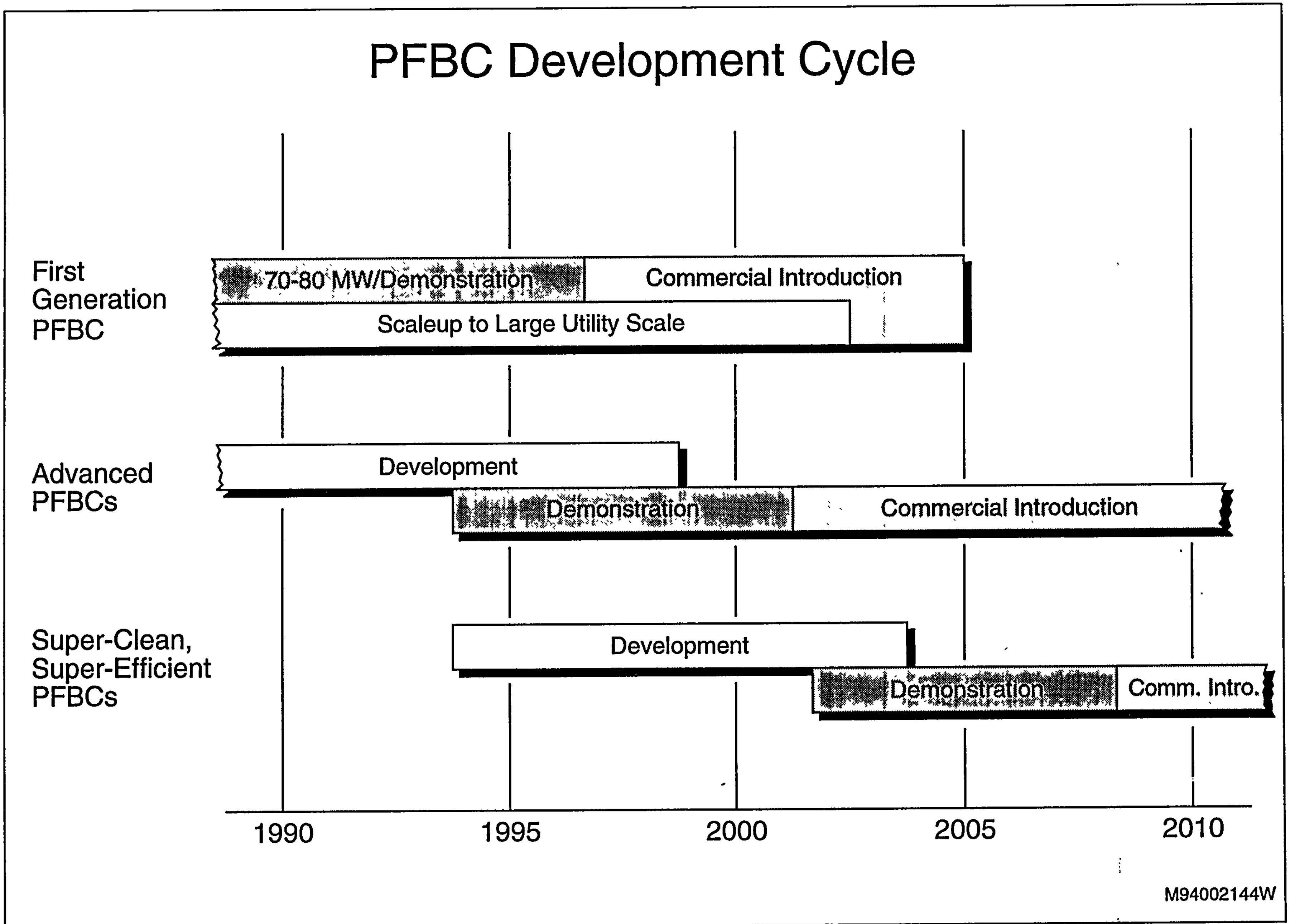

Figure 2 Current Development Schedule for the Pressurize Fluid-Bed Program

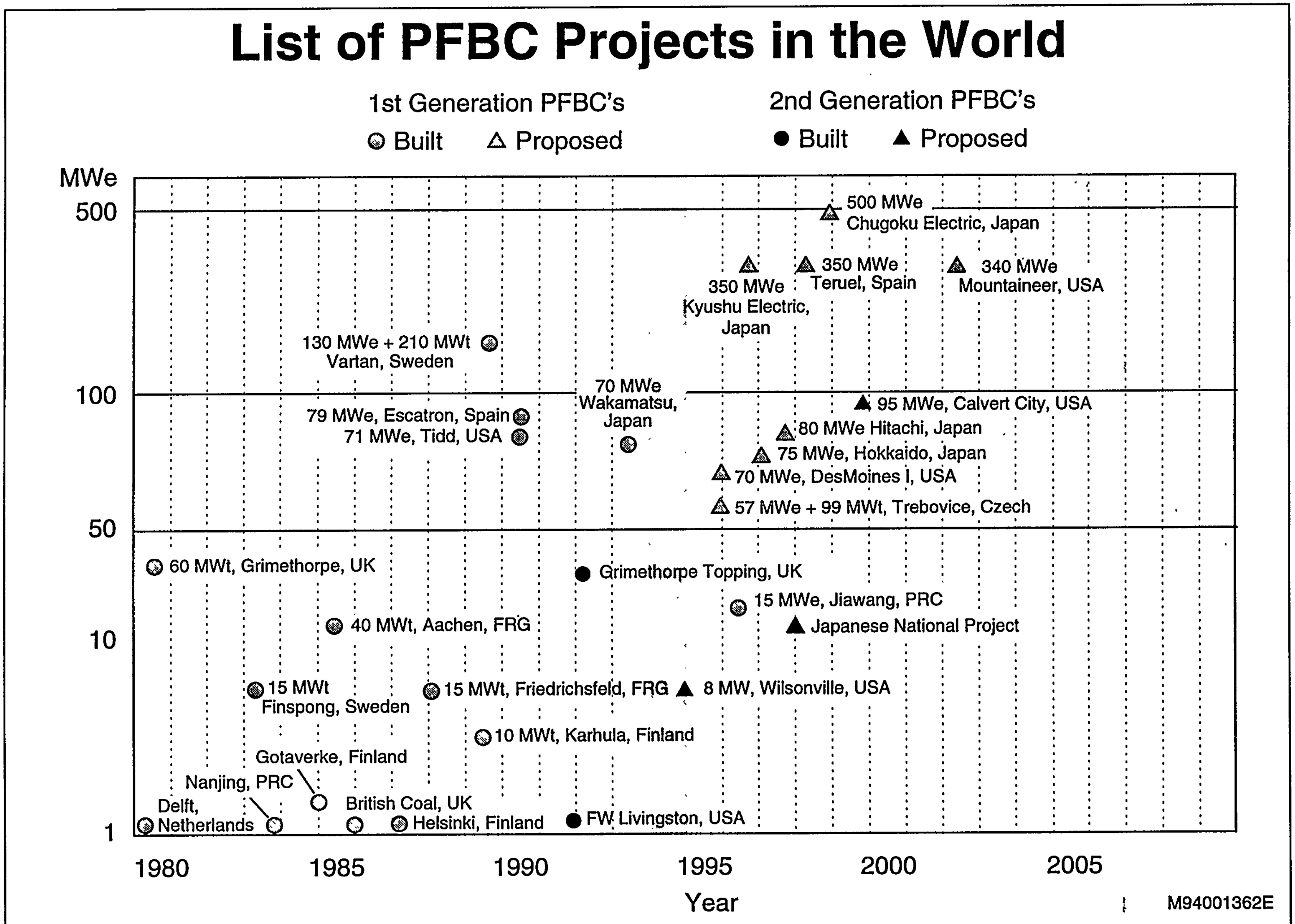

Figure 3 Pressurized Fluid-Bed Combustion Systems Built or Planned World Wide Displayed by System Type, Generation Capacity, and Year of Operation.

	Second Gen. PFBC	PFBC with adv. Gas T.	PFBC with adv. Steam T.	PFBC with adv. GT & ST	PFBC with 2nd B.C.	PFBC with B.C. & Chiller	PFBC with B.C., F.C., Chiller	Complete SPFBC
Gas Turbine (MW)	139.4	156	139.5	155.5	139.4	148.6	156.5	141.3
Steam Turbine	138.3	131.4	173.4	165	138.3	132.2	98.4	185
Second Bottoming Cycle	0	0	0	0	19.4	18.6	17.5	18.9
Fuel Cell System	0	0	0	0	0	0	48.3	26.9
Inlet Air Chiller	0	0	0	0	0	-1.5	-1.7	-1.2
Misc.	-3.5	-3.4	-5.9	-5.6	-3.5	-3.3	-2.7	-6.6
Auxiliary	-5	-5.2	-5.6	-5.8	-5.4	-5.4	-5.4	-6.6
Total Megawatts	269.3	278.9	301.3	309.1	288.3	289.1	310.9	357.8
Efficiency (HHV %)	46.5	48.2	52.1	53.4	49.8	50	53.7	61.8
Gas Turbine (T)	2300	2450	2300	2450	2300	2300	2300	2450
Steam Turbine (P)	2400	2400	4500	4500	2400	2400	2400	4500
Second Bottoming Cycle	N	N	N	N	Y	Y	Y	Y
Fuel Cell System	N	N	N	N	N	N	Y	Y
Inlet Air Chiller	N	N	N	N	N	Y	Y	Y

Table 1 Pressurized Fluid-Bed Combustion System Simulations Establish the Effect of Each of the Proposed Super-Clean Super-Efficient PFBC Sub-Systems.