Startup and Shutdown NO_x Emissions from Combined-Cycle Combustion Turbine Units

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Abstract

During the course of the Electric Power Research Institute's (ERPI) ongoing "Low NO_x Emissions Measurement" project, it became clear that the startup and shutdown emissions of NO_x from these same ultra-low NO_x combined-cycle units were being addressed on a more detailed and parameter-specific basis. Depending on the state air regulatory authority issuing the permit in question, the startup and shutdown emissions provisions and conditions may vary significantly in scope and stringency. This paper serves to investigate, on a preliminary basis, startup and shutdown NO_x emissions on a manufacturer, permit, and NO_x CEMS basis in order to answer the underlying question – *are these permit limits accurate, representative, and reasonable?*

Introduction and Background

Just over two years ago, RMB Consulting & Research, Inc. (RMB) began research, in conjunction with EPRI, concerning "ultra-low" emission levels of nitrogen oxides (NO_x) from gas-fired (and oil-fired) combined-cycle combustion turbine units. All of these newly constructed combined-cycle units are required to install continuous emissions monitoring systems (CEMS) to continually measure, record, and report NO_x emissions to demonstrate compliance with local, state, or federal air emission limits, as well to quantify emission allowances under EPA's Acid Rain Program.

While these ultra-low levels of NO_x present monitoring challenges of their own, ranging from the accuracy of the measurements to the regulatory conflicts and discrepancies created by numerous sets of rules, it was learned during the course of this research that an additional issue has been raised – that issue being the startup and shutdown emissions from these same ultra-low NO_x combined-cycle units.

For any given combined-cycle unit with an ultra-low NO_x permit limit typically ranging from 2–5 ppm NO_x (or lower), it is an understood and accepted fact that the low NO_x limit is a steady-state, controlled limit made possible by proper combustion and control technology practices. Startup and shutdown emissions, on the other hand, are not steady-state emissions and are not controlled (i.e., from a control technology standpoint), and, as a result, are significantly higher and extremely more random than those emissions under controlled operation. During RMB's research, it had become apparent that, over time, some state air regulatory agencies have been making the startup and shutdown provisions contained in their air permits more and more specific, complicated, and stringent.

The natural laws of physics and chemistry dictate that uncontrolled NO_x emissions at levels significantly higher than NO_x emissions at the steady-state, controlled level are impossible to avoid during startup and shutdown periods. This preliminary, topical report serves to investigate in greater detail the varying schools of thought and perspectives of startup and shutdown emission values and how accurate, representative, and reasonable they are with respect to the limits prescribed in air permits currently being issued. For the purposes of this report, an initial attempt has been made to compare startup and shutdown emissions from (1) the turbine manufacturer's suggested values versus (2) prescribed air permit limits versus (3) what is monitored by the facility-installed NO_x CEMS.

Principles of Operation

Startup and shutdown periods serve to thermally stabilize a given unit to ensure efficient and proper operation of the unit. In order to understand the concept of startup and shutdown emissions for any given combustion turbine unit, it is first necessary to describe and explain the basic principles for how combined-cycle unit operation is either started or stopped.

The primary components of a given combined-cycle unit (or plant) are comprised of a gas (or combustion) turbine, steam turbine, heat recovery steam generator (HRSG), and NO_x control device (typically selective catalytic reduction, or SCR). Some combined-cycle units also employ the use of duct burners in the HRSG for supplemental firing. The fundamental operating concept of a combined-cycle unit is to generate power from the gas turbine, and to additionally recover and transfer high temperature gas turbine exhaust energy to a steam turbine for further power generation (and increased efficiency). Typical combined-cycle designs use either 1, 2, or 3 gas turbines per steam turbine. Moreover, when speaking of the emissions from a combined-cycle unit, the emissions are in reference to those emitted via the gas turbine(s) exhaust stack.

One of the advantages of using a combined-cycle unit is its relatively short startup and shutdown time as well as quick load change capability. Granted, by short startup time, it is not implied to be like that of flicking a light switch or starting an automobile. But in power generation terms, it is a relatively short period of time when compared to a more "traditional" source of power such as that provided by a coal-fired utility boiler.

Modern combined-cycle units have different startup times depending upon the amount of time that the unit has "stood still" or has not been operating since its last period of operation. These standstill periods result in start-types that are referred to as either cold, warm, or hot startups.

While the standstill definitions may vary depending upon the make and model of the unit in question, generally speaking, a cold start is made after a standstill period of > 72-120+ hours (3-5 days or more); a warm start is made after a standstill period of > 48-60 hours (2-3 days); and a hot start is made after a standstill period of ≤ 8 hours. As you can see from the above definitions, there remains a "gray area" as to what type of start is defined after a standstill period of 8-48 hours and 60-72 hours.

A combined-cycle startup procedure is separated into three (3) primary phases:

(1) purging of the HRSG
(2) gas turbine speed-up, synchronization, and loading
(3) steam turbine speed-up, synchronization, and loading

The gas turbine portion of a combined-cycle unit is independent of the standstill time, allowing up to two-thirds of the power to be available within 30 minutes of activating a startup event. 50-60% of gas turbine load is the level at which the appropriate steam properties for steam turbine startup are reached. The HRSG and steam turbine, however, take varying amounts of time to startup, depending upon how long the unit was not in operation prior to startup. The steam turbine contains parts in the machine that take time to heat up and prepare for normal operation, all without introducing thermal stresses onto these components. Standstill time is very significant for steam turbine use and determines what temperature these parts are at when a startup event is begun – obviously, the longer the standstill time, the longer the subsequent startup time. (Note that the HRSG and steam turbine are the primary reasons for longer startup times associated with combined-cycle unit operation, as opposed to simple-cycle units that use a combustion turbine only, and hence have much shorter and consistent startup times.)

Once the unit is brought to a load of typically > 50% and the HRSG temperature at the SCR grid reaches a temperature of approximately 575 ^{o}F (which is the temperature at which the SCR system can be activated), the startup period/event can end and normal combustion practices and control technology operation can begin. As a result, steady-state, controlled emissions of NO_x can then be achieved.

In order to shutdown a combined-cycle unit, gas turbine load is reduced. Similar to that of a startup period, a shutdown period is usually that of 50% load and lower. Once the exhaust gas temperature of the gas turbine has lowered to a prescribed minimum level, the steam turbine is then shut down. The gas turbine is further "unloaded" and ultimately shut off.

Air Permit Evolution

Since approximately 1999, it has been noticed that state air regulatory agencies have been making the startup and shutdown provisions contained in the air permits more and more specific, complicated, and stringent. That is, depending upon the state, startup and shutdown permit conditions have evolved from (1) being generally mentioned or addressed, to (2) containing time restrictions (either in hours or minutes per startup/shutdown event), and eventually to (3) containing both time restrictions as well as NO_x concentration and/or mass emissions limits.

EPRI's technical report *"Monitoring Low NO_x Emissions: Style Requirements for Research Contractors," EPRI, Palo Alto, CA: 2001. 1004594.* briefly touched upon this concept. The three following conditions/provisions provide examples of the steadily evolving language contained in a typical combined-cycle unit permit for startup/shutdown events:

- "The emission standards of [the previously mentioned provisions for steady-state, controlled operation] apply except during startup, shutdown, and load change."

- "Gas turbine shall operate at less than 75% load during startups and shutdowns as follows: "hot start" = 90 minutes; "cold start" = 4 hours; "shutdown" = 90 minutes. "Hot start" is startup after 24 hours or less downtime and "cold start" is startup after greater than 24 hours of downtime. SCR controls shall operate when turbine is operated at 50% load or greater. The short-term emission limits do not apply during "startup" and "shutdown" periods."

- "The startup time includes 250 minutes for a cold start and 90 minutes for a hot start per turbine. The shutdown emissions include a time of 60 minutes per turbine…NO_x emissions are limited to 202 lbs/hr during startup [does not clarify whether that is a maximum value or an average value] and 103 lbs/hr during shutdown…no more than two startup/shutdown cycles are permitted on a daily basis."

These permit conditions are taken from three different air permits for units located in three different states. Note how the permit conditions increase in complexity and stringency for these three example conditions. While not exact, this pattern has seemed to evolve from one level to the next over the past three years, with the first condition being a "1999 condition," the second a "2000 condition," and the third a "2001 and beyond condition."

The problem at hand, however, is not really the growing *stringency or complexity* of these conditions, but rather the *accuracy and appropriateness* of them. Not only do startup/shutdown emissions differ between simple-cycle and combined-cycle units (mainly because of the time it takes to "warm up" a given unit), but they also differ depending upon the make and model of the unit. From a regulatory agency perspective, it is understandable that states may want to incorporate startup/shutdown conditions for PSD/offset/attainment, modeling, annual emission inventory, rolling average, or emission allowance (under the Acid Rain and/or NO_x Budget Programs) purposes. However, it should be made perfectly clear to the state permitting authorities that make, model, size, and cycle be taken into account as opposed to randomly pulling numbers out of the air or generically inserting requirements for "all" units, just because "it's a turbine." The following sections serve to demonstrate the fact that, depending upon what make and model of the machine or whom you ask, startup/shutdown emissions are by no means a standardized set of values.

Discussion of Results

What Do The Manufacturers Say?

Tables 1, 2, and 3 provide startup and shutdown data as provided by the turbine manufacturer. The data included here is for a General Electric (GE) Model 7241FA (more commonly referred to as the GE 7FA), a GE Model 207FA, and an Asea Brown Boveri (ABB) Model KA24-1, respectively.

Table 1. Startup/Shutdown Data As Provided By Turbine Manufacturer –
GE 7241FA (aka GE 7FA) Combined-Cycle Combustion Turbine Mode

COLD STARTUP[1]					
Time (min)	**CT Load (%)**	**NO_x Control (%)**	**NO_x Emissions (ppm @15% O_2)**	**Instantaneous NO_x Emissions (lb/hr)**	**Cumulative NO_x Emissions (lb)**
0	0	0	0.0	0	0
20	Flame On	0	0.0	0	0
29	On-line	0	65.0	97	10
30	8	0	**75.0 (high value)**	150	12
60	8	0	**75.0 (high value)**	150	87
61	8	50	37.5	75	89
177	8	50	37.5	75	234
180	10	50	25.0	50	237
183	12	50	27.5	60	240
194	22	50	42.5	110	255
196	25	50	35.0	100	259
199	40	50	50.0	175	266
200	40	50	50.0	175	269
202	50	50	52.5	**225 (high value)**	275
~202 min/cs[2]	50	61	*3.5 (controlled)*	15	**275 lbs/cs**
209	70	61	*3.5 (controlled)*	16	277 lbs/cs
SHUTDOWN					
0	100	61	*3.5 (controlled)*	24	0
10	25	61	27	78	9
15	25	61	27	78	15
19	Flame Off	0	**65 (high value)**	**97 (high value)**	21
~30 min/sd[3]	0	0	0	0	**30 lbs/sd**

[1]Values represent testing @ ISO conditions, 59 °F ambient temperature, 60% relative humidity, and 14.7 psia atmospheric pressure.
[2]cs = cold startup event
[3]sd = shutdown event

Table 2. Startup/Shutdown Data As Provided By Turbine Manufacturer – ***GE 207FA Combined-Cycle Combustion Turbine Mode***

COLD STARTUP (after 72 hour shutdown)		WARM STARTUP (after 48 hour shutdown)		HOT STARTUP (after 8 hour shutdown)	
Time (min)	**CT Load (%)**	**Time (min)**	**CT Load (%)**	**Time (min)**	**CT Load (%)**
0	0	0	0	0	0
28	0	28	0	26	0
30	8	30	10	28	10
165	8	72	10	31	20
166	10	75	20	60	20
171	20	79	30	62	30
176	30	82	40	63	40
181	40	85	50	65	50
185	50	88	60	66	60
190	60	91	70	67	70
195	70	95	80	69	80
199	80	98	90	70	90
204	90	101	100	72	100
210	100	—	—	—	—
~185 min/cs[1]		**~85 min/ws[2]**		**~65 min/hs[3]**	

[1]cs = cold startup event
[2]ws = warm startup event
[3]hs = hot startup event

Table 3. Startup/Shutdown Data As Provided By Turbine Manufacturer – ***ABB KA24-1 Combined-Cycle Combustion Turbine Mode***

COLD STARTUP (after 72 hour shutdown)		WARM STARTUP (after 48 hour shutdown)		HOT STARTUP (after 8 hour shutdown)		SHUTDOWN	
Time (min)	**NO_x (lb/cs)**	**Time (min)**	**NO_x (lb/ws)**	**Time (min)**	**NO_x (lb/hs)**	**Time (min)**	**NO_x (lb/sd)[1]**
105	79	98	55	41	23	36	19

[1]sd = shutdown event

Based upon manufacturer data, a cold startup of a GE Model 7FA is estimated to take approximately 202 minutes with a cumulative NO_x mass emission value of 275 lbs/cold start, otherwise known as lbs/event. The highest NO_x ppm value is 75 ppm (corrected to 15% O_2), which occurs from approximately the 30 to 60 minute mark during startup. Note that the highest NO_x ppm value does not necessarily correspond to the highest instantaneous NO_x lb/hr emission rate; this is because NO_x lb/hr is dependent not only upon NO_x ppm, but also upon the O_2 concentration and heat input (in mmBtu/hr) at any given time. For this particular set of data, the highest instantaneous NO_x lb/hr rate of 225 lb/hr occurs just prior to the conclusion of the startup period (i.e., where the heat input would be at its highest "uncontrolled NO_x level"). Shutdown events are estimated to take approximately 30 minutes, with a cumulative NO_x mass emission value of 30 lbs/shutdown.

Similarly, a cold startup of a GE Model 207FA is estimated to take approximately 185 minutes. Warm startups and hot startups are estimated to take 85 minutes and 65 minutes, respectively.

For the ABB Model KA24-1, a cold startup is estimated to take approximately 105 minutes with a cumulative NO_x mass emission value of 79 lbs/cold start. Warm startups are estimated to take approximately 98 minutes with a cumulative NO_x mass emission value of 55 lbs/warm start, and hot startups are estimated to take approximately 41 minutes with a cumulative NO_x mass emission value of 23 lbs/shutdown. Again, as mentioned previously, depending upon the make and model of the unit, the length of time or the mass emissions for a particular event will vary.

Three additional and significant items to note are the fact that these data are derived from theoretical rather than empirical curves – meaning, these data are based upon what the manufacturer thinks *should happen* as opposed to what *does happen*. Secondly, if not already noted as part of Table 1, those data values represent ISO conditions, 59 ^{o}F ambient temperature, 60% relative humidity, and 14.7 psia atmospheric pressure – i.e., standardized, constant conditions. Unless a GE 7FA is located in a magical place where nature is asleep and the atmospheric conditions are always identical, these values will most certainly change. The bottom line is that these values do change depending upon atmospheric conditions, and air permits should take that into account. Last and most importantly, the data shown in the above tables are provided by the manufacturer as typical values and ***are not guaranteed***. These values are considered estimates due to the extremely transitory nature of these machines, and confidence in the accuracy of the data is much lower than for higher, more stable, and controlled operating loads. While having limits placed into an air permit that "are not guaranteed" is another story for another time, it goes without saying that prudence should be exercised and limits erring on the side of conservatism should be placed into the subject permit before the source signs on the dotted line.

What Do The Air Permits Say?

Table 4 provides a compilation of startup and shutdown requirements, as contained in air permits, for various combined-cycle units located throughout the United States (some permit limits are for permits issued within the same state). Manufacturers include GE, Westinghouse, and ABB, who are three of the more common manufacturers of these types of units. The data included are for GE Models 7FA and 207FA, Westinghouse Models 501FC and 501FD, and ABB Models GT11N2 and GT-24 OTC. In addition to the various makes and models contained in the table, different unit sizes were also taken into account and listed.

Table 4. Startup/Shutdown Limits As Contained In Various Air Permits For Different Combined-Cycle Unit Makes, Models, and Sizes

Make & Model	Electrical Output (MW)[1]	Startup Time (min)	Shutdown Time (min)	Startup NO_x Emissions	Shutdown NO_x Emissions
GE 7241FA (aka 7FA)	170 (x2) + 160	180 (cold) 120 (warm) 60 (hot)	None listed	20 lbs/hr 60 lbs/cs[2] 40 lbs/ws[3] 20 lbs/hs[4]	None listed
	166 (x2) + 171	240 (cold) 120 (hot)	60	76 lbs/hr 152 lbs/cs 304 lbs/hs	None listed
	165 (x2) + 175	40 (all)	40 (all)	73 lbs/hr 49 lbs/su[5]	73 lbs/hr 49 lbs/sd[6]
	185 (x2) + 155	250 (cold) 180 (warm) 90 (hot)	60	202 lbs/hr 842 lbs/cs 606 lbs/ws 303 lbs/hs	103 lbs/hr 103 lbs/sd
	175 (x2) + 240	256 (all)	23	170 lbs/hr 725 lbs/su	72 lbs/hr 28 lbs/sd
	167 (x2) + 285	240 (all)	240	80 lbs/hr 320 lbs/su	80 lbs/hr 320 lbs/sd
	168 (x3) + 185	217 (cold) 60 (hot)	30	46 lbs/hr (cold) 107 lbs/hr (hot) 166 lbs/cs 107 lbs/hs	100 lbs/hr 50 lbs/sd
GE 207FA	170 (x2) + 180	120 (all)	30	223 lbs/hr 446 lbs/su	58 lbs/hr 29 lbs/sd
Westinghouse 501FC	170 (x2) + 160	180 (cold) 60 (hot)	60	170 lbs/hr 510 lbs/cs 170 lbs/hs	12 lbs/hr 12 lbs/sd
	165 (x2) + 170	180 (all)	180 (all)	None listed	None listed
Westinghouse 501FD	200 (x2) + 235	180 (cold) 60 (hot)	30	80 lbs/hr 240 lbs/cs 80 lbs/hs	18 lbs/hr 9 lbs/sd

[1]Each set of electrical output values includes the MW values for the gas/combustion turbine(s) (along with the # of gas/combustion turbines) + the MW value of the steam turbine. Each set of electrical output values represents an individual, unique combined-cycle system. *[For example, the first system listed is a General Electric Model 7FA comprised of 2 gas/combustion turbines rated at 170 MW each, and are both attached to the same steam turbine, which is rated at 160 MW. The "2x1" design results in a combined-cycle system rated at 500 MW total.]*
[2]cs = cold startup event
[3]ws = warm startup event
[4]hs = hot startup event
[5]su = startup event (does not differentiate between cold, warm, or hot)
[6]sd = shutdown event

Table 4 *continued*. Startup/Shutdown Limits As Contained In Various Air Permits For Different Combined-Cycle Unit Makes, Models, and Sizes

Make & Model	Electrical Output (MW)[1]	Startup Time (min)	Shutdown Time (min)	Startup NO_x Emissions	Shutdown NO_x Emissions
ABB GT11N2	110 (x1) + 60	240 (cold) 90 (hot)	90	None listed	None listed
ABB GT-24 OTC	172 (x1) + 90	120 (cold) 30 (warm) 30 (hot)	24	36 lbs/hr (cold) 88 lbs/hr (warm) 36 lbs/hr (hot) 72 lbs/cs 44 lbs/ws[6] 18 lbs/hs	164 lbs/hr 66 lbs/sd
	175 (x1) + 100	120 (all)	None listed	7 lbs/hr (cold) 9 lbs/hr (warm) 9 lbs/hr (hot) 14 lbs/cs 18 lbs/ws 18 lbs/hs	None listed

Based upon the preceding table, a startup of a given GE Model 7FA is permitted at lengths of time ranging from less than or equal to 40 minutes all the way up to 256 minutes (for cold, warm, and hot startup conditions). Cumulative NO_x mass emission values have permitted ranges from 49 to 725 lbs/startup event. Permitted NO_x emission rates range from 20 to 202 lbs/hr (though it is often unclear whether those are average values or maximum, instantaneous values). Shutdown events are permitted at levels ranging between 23 and 240 minutes. Likewise, cumulative NO_x mass emission values have permitted ranges from 28 to 320 lbs/shutdown event. Permitted NO_x emission rates range from 72 to 103 lbs/hr.

For the remaining makes and models of combined-cycle units, the same unpredictable and curious trends apply. That is, values of startup and shutdown times as well as NO_x emission rates and cumulative emissions vary, with no distinguishable or definable pattern.

What Does The NO_x CEMS Say?

Tables 5, 6, and 7 provide startup and shutdown data as monitored "in real-life" by certified NO_x CEMS under EPA's Acid Rain Program (40 CFR Part 75). The data included here are for a GE 7FA as well as Westinghouse Models 501FD and 501F (with the 501F model being a simple-cycle as opposed to a combined-cycle unit).

Table 5. Startup/Shutdown Data As Monitored By NO_x CEMS –
GE 7241FA (aka GE 7FA) – 170 MW Units (Combined-Cycle Configuration)

Unit	Event	Start Type	Hours Down Prior To Event	Event Length (min)	Maximum NO_x During Event (ppm @15% O_2)	Heat Input @ Max. NO_x (mmBtu/hr)	Emission Rate @ Max. NO_x (lb/hr)
A	SU #1	warm	45	≤ 240	52.8	821.8	159.9
	SU #2	cold	155	~11 hrs	53.0	736.3	143.8
	SU #3	warm	26	≤ 240	43.5	566.9	90.8
	SU #4	hot	6	≤ 240	44.6	635.6	104.4
	SU #5	warm	32	≤ 240	46.6	648.5	111.3
	SU #6	cold	96	≤ 240	41.8	439.7	67.7
	SD #1	N/A	N/A	≤ 30	3.9	666.4	9.6
	SD #2	N/A	N/A	≤ 60	48.7	820.0	147.1
	SD #3	N/A	N/A	≤ 60	14.9	1212.8	66.6
	SD #4	N/A	N/A	≤ 45	17.9	307.4	20.3
	SD #5	N/A	N/A	≤ 60	10.2	1282.2	48.2
	SD #6	N/A	N/A	≤ 60	13.8	1069.6	54.4
B	SU #1	hot	0.75	≤ 180	47.7	826.8	145.3
	SU #2	hot	6	≤ 180	24.4	526.2	47.3
	SU #3	cold	180	~14 hrs	82.8	968.0	295.3
	SU #4	warm	25	≤ 240	43.9	525.1	84.9
	SU #5	warm	29	≤ 180	43.7	499.3	80.4
	SU #6	cold	89	~8 hrs	53.8	1157.2	229.4
	SD #1	N/A	N/A	≤ 75	49.6	185.9	34.0
	SD #2	N/A	N/A	≤ 90	172.9	516.8	329.2
	SD #3	N/A	N/A	≤ 90	23.4	80.1	6.9
	SD #4	N/A	N/A	≤ 75	43.6	23.2	3.7
	SD #5	N/A	N/A	≤ 30	19.6	192.8	13.9
	SD #6	N/A	N/A	≤ 30	44.2	76.8	12.5
C	SU #1	cold	167	~7 hrs	56.6	1486.1	309.9
	SU #2	cold	332	~5 hrs	50.8	1049.5	196.4
	SD #1	N/A	N/A	≤ 60	10.3	1486.1	56.4
	SD #2	N/A	N/A	≤ 30	27.7	306.0	31.2
D	SU #1	cold	629	≤ 240	54.6	752.4	151.3
	SU #2	cold	321	~9 hrs	48.5	713.9	127.6
	SD #1	N/A	N/A	~9 hrs	101.9	977.3	366.9
	SD #2	N/A	N/A	≤ 60	20.5	795.5	60.1

Table 6. Startup/Shutdown Data As Monitored By NO_x CEMS –
Westinghouse 501FD – 160 MW Units (Combined-Cycle Configuration)

Unit	Event	Start Type	Hours Down Prior To Event	Event Length (min)	Maximum NO_x During Event (ppm @15% O_2)	Heat Input @ Max. NO_x (mmBtu/hr)	Emission Rate @ Max. NO_x (lb/hr)
A	SU #1	?	unknown	65	31.2	932.8	107.2
	SU #2	?	unknown	96	27.1	911.6	91.0
	SU #3	?	unknown	131	180.3	776.9	516.0
	SD #1	N/A	N/A	26	14.6	535.9	28.8
	SD #2	N/A	N/A	17	10.9	1119.3	44.9
	SD #3	N/A	N/A	17	10.8	1117.8	44.5
B	SU #1	?	unknown	73	32.9	1075.3	130.3
	SU #2	?	unknown	104	32.4	976.1	116.5
	SU #3	?	unknown	66	29.8	952.6	104.6
	SD #1	N/A	N/A	19	12.9	1662.0	79.0
	SD #2	N/A	N/A	26	13.9	523.1	26.8
	SD #3	N/A	N/A	14	17.3	571.3	36.4

Table 7. Startup/Shutdown Data As Monitored By NO_x CEMS –
Westinghouse 501F – 170 MW Unit (Simple-Cycle Configuration)

Unit	Event	Start Type	Event Length (min)	Maximum NO_x During Event (ppm)	Heat Input @ Max. NO_x (mmBtu/hr)	Emission Rate @ Max. NO_x (lb/hr)	NO_x Mass Emissions (lb/event)
A	SU #1	hot	24	29.0	1043.4	120.2	13.2
	SU #2	hot	23	38.8	981.8	152.3	14.7
	SU #3	hot	21	41.2	985.9	161.3	15.4
	SD #1	N/A	21	15.0	1239.7	65.9	11.8
	SD #2	N/A	20	33.7	942.4	133.2	22.4
	SD #3	N/A	19	33.0	942.0	132.5	20.3

Table 5 shows data for four (4) different 170 MW GE Model 7FAs. The NO_x CEMS data in the table shows that "typical" startup events were completed in either less than 240 minutes or 180 minutes. However, for periods where the units were shutdown for over 150 hours ("very cold" starts), startup events often lasted well more than 240 minutes, with some of the startups taking up to 14 hours before the unit was up to a suitable load and properly controlled. The NO_x ppm values ranged from 24 to 83 ppm, with the corresponding, instantaneous NO_x lb/hr readings (at high NO_x, not high heat input) ranging from 47 to 310 lb/hr. Shutdown periods were shown to typically take less than 30 or 60 minutes; some shutdown events, however, lasted between 60 and 90 minutes. The NO_x ppm values ranged from 4 to 173 ppm, while the instantaneous NO_x lb/hr readings ranged from 10 to 367 lb/hr.

Tables 6 and 7 show data for two Westinghouse 501F Series combined-cycle units and one simple-cycle unit, respectively. For the combined-cycle units, startup events ranged from 65 to 131 minutes, NO_x ppm values ranged from 27 to 180 ppm, and the instantaneous NO_x lb/hr readings ranged from 91 to 516 lb/hr. Shutdown periods were shown to each take less than 30 minutes. For the simple-cycle unit, startup events ranged from 21 to 24 minutes, NO_x ppm values ranged from 29 to 41 ppm, and the instantaneous NO_x lb/hr readings ranged from 120 to 161 lb/hr. Shutdown periods were shown to each take less than or equal to 21 minutes. For the simple-cycle unit, 1-minute data were also available, yielding NO_x mass emissions of 15.4 lb/startup and 22.4 lb/shutdown. Notice also that, because of the nature of simple-cycle units (i.e., where a secondary steam turbine is not part of the design), the startup cycles take less time (and hence emits less NO_x). Moreover, the startup versus the shutdown emissions are generally the same for the simple-cycle machine.

Comparison of Values

Table 8 summarizes a comparison between the lengths of time associated with cold startup and normal shutdown events for the GE Model 7FA. The comparison is made by taking the data provided in the prior tables based upon the manufacturer, air permit, and NO_x CEMS results.

Table 8. Comparison of Length of Events – *General Electric 7FA*

Source	Length of Cold Startup Event (min)			Length of Shutdown Event (min)		
	Low End	High End	Typical	Low End	High End	Typical
GE	—	—	202	—	—	30
Permit	40	256	180-240	23	240	30-60
NO_x CEMS	≤ 240	840	≥ 240	≤ 30	≤ 90	≤ 60

What Table 8 shows is that the NO_x CEMS data in question are *generally* similar to the data provided by GE or to those limits imposed in a particular air permit. However, there are certainly instances in which the actual data are greater than that suggested by the manufacturer or air permit. In fact, many examples have been shown where a cold startup of a GE 7FA machine takes longer (in some cases much longer) than the theoretical value of 202 minutes per cold startup. Similarly, a typical shutdown period has been shown to take between 30 and 60 minutes, which is greater than the manufacturer suggested value of 30 minutes. For those cases where the lengths of a startup or shutdown event are shown to be greater than that in an air permit limitation, a permit notice of violation will most likely be issued and subsequent regulatory enforcement may result. More disturbing is the fact that GE has suggested 202 minutes per cold startup and 30 minutes per shutdown, yet some permits are being issued with values lower than those suggested (i.e., 40 and 23 minutes, respectively).

NOTE: For all of the previous tables where certain data appear to be missing or incomplete, it is more than likely because the data were unavailable at the time of preparing this report.

Conclusions and Recommendations

Startup and shutdown data from combined-cycle units vary tremendously, whether they are from different makes and models or the same make and model. For the same make and model, it could be either two (or more) different units at different facilities or even the exact same unit at the same facility. Moreover, depending upon your point of reference, whether it be the manufacturer, permitting authority, or NO_x CEMS, these values will differ. Even within the state regulatory agencies, there appears to be no pattern or general consensus as to what these values should be.

However, what the data suggests is what many have known all along and comes as no surprise. Since startup and shutdown periods are uncontrolled and are mainly a result of the laws of turbine mechanics, chemistry, physics, and mother nature, those emissions *"are what they are"* and will vary. Emissions during startup and shutdown periods cannot be further controlled beyond the best operational practices that will already be employed and are beyond any unit operator or regulatory authority's control. That is, ***startup and shutdown emissions will be the same (albeit random) whether there is a permit condition or not***.

In short, as opposed to control devices such as SCRs or water injection which are used for the intent of reducing emissions for NSPS/BACT purposes, startup and shutdown limits really do not accomplish or solve anything nor serve any real purpose. Just because a certain emission limit in ppm, lb/event, or period of time is allotted and included in a source's air permit, that does not mean that the unit will (or can) operate under these limits, or achieve steady-state, normal operation by the end of that permit's decreed grace periods. Moreover, failing to fall within these limits does not imply negligence, improper unit operation, or an outright disregard for a given set of permit limits and conditions.

As mentioned previously, it is understood that states may want to incorporate startup/shutdown conditions for PSD, emission inventory, rolling average, or emission allowance purposes, etc. Meaning, there *are* justifications for quantifying startup and shutdown mass emissions, and it is not the intent of this paper to suggest otherwise. However, those purposes can be satisfied without having to insert specific limitations into a permit. For those states, though, that may desire to put actual startup and shutdown limits into the permits, make, model, size, and cycle data need to be taken into account as opposed to inserting random or generic requirements. Unfortunately, for makes and models where emissions data are not available, some states have even resorted to using available simple-cycle data and multiplying those data by mythical emission factors of approximately 1.5. This is a perfect example of "making up numbers" and should be considered unacceptable because it is fundamentally unsound.

It is imperative that the appropriate language regarding the startup and shutdown of a given unit or set of units be properly negotiated during the initial permit application and writing process. Reasonable and conservative lengths of time, feasible NO_x limits, historical data, and the fundamental laws of physics and chemistry must be considered. Provisions should also be included in every combustion turbine air permit that exclude unavoidable, random, and atypical emissions (whether in ppm, lbs, or minutes), especially for cold startup/long downtime periods (as shown in Table 5). In addition, language should also be incorporated into the air permit allowing for the adjustment of the permit limits should those limits not be sufficient, either after an established operating history or once a stack testing program has been completed.

Note that the two most significant parameters are (1) the length of a given event (in minutes) and (2) the amount of NO_x mass emissions of a given event (lb/event). NO_x lb/event certainly seems to be a more appropriate representation of the NO_x emissions as opposed to NO_x ppm or an instantaneous reading of NO_x lb/hr. NO_x ppm or lb/hr values can be misleading at times since the O_2 concentration (and subsequent lb/mmBtu emission rate, which may or may not be relatively high) is not taken into account, nor is the heat input of the unit during a time of "high" NO_x ppm. Relatively high and instantaneous NO_x lb/hr values are "snapshots" of the NO_x emissions at that particular point in time and, over time, will be lower and average out to more representative levels. For those permits where startup and shutdown emissions are to be measured, quantifying those emissions in terms of lb/event certainly seems to be the most representative approach to take.

Other recommendations are as follows:

- If the permit is to contain limits for cold, warm, and hot startups, definitions as to what constitutes a certain startup category should be included (e.g., a "cold" startup is defined as a startup after 72 hours of downtime, etc.).
- For those permits where ppm is to be listed, it should be made clear whether or not that ppm value is to be corrected to 15% O_2.
- The only time uncorrected NO_x ppm should be taken into account is to determine whether or not the ppm value has exceeded the range/span of the analyzer.
- NO_x lb/hr limits should distinguish between average (or rolling) lb/hr or maximum allowable lb/hr. For rolling averages, it should also be clarified if off-line periods (in other words, 0.0 lb/hr) should be considered.
- If the permit has a daily NO_x lb/hr rolling-average limit, it should state whether or not startup and shutdown events are to be averaged in.
- The fact that manufacturer data is not guaranteed (under 50% load) as well as varying atmospheric conditions should be taken into account.
- Simple-cycle startup data should not be used to determine combined-cycle startup values.
- The air permit should clearly state whether or not the emission limits are per each combustion turbine or group of turbines.
- The firing of different/multiple fuels should be considered.

Future Efforts

This preliminary, interim report serves as an introduction to the results obtained by way of performing a three-way analysis between manufacturer, air permit, and NO_x CEMS data for startup and shutdown emissions, as well as a summary of the associated issues for those types of emissions.

A more comprehensive report is tentatively due to EPRI in September 2002. For the final report, it is hoped that more manufacturer make and model data can be provided, especially in terms of min/event and lb/event. In addition, RMB is currently expecting more NO_x CEMS data from various client contacts. The forthcoming NO_x CEMS data are going to concentrate on 1-minute values in order to more accurately quantify min/event and lb/event, since these are the two primary parameters used as air permit limits. Obviously, the more data the better, and any manufacturer, CEMS operator, or plant representative willing to anonymously volunteer data for this endeavor would be much appreciated. Please contact RMB for further information.