CHAPTER 5. ENGINEERING ANALYSIS

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

CHAPTER 5. ENGINEERING ANALYSIS

5.1 INTRODUCTION

The engineering analysis establishes the relationship between manufacturer production cost (MPC) and energy consumption for the automatic commercial ice makers covered in this rulemaking. The “cost-efficiency” relationship serves as the basis for cost-benefit calculations in terms of individual customers, manufacturers, and the Nation, from which the most economically justified, technologically feasible standard level is ultimately determined.

The inputs to the engineering analysis include baseline characteristics for each equipment class addressed in the market and technology assessment (chapter 3 of the preliminary technical support document (TSD)), the design options from the screening analysis (chapter 4), as well as cost and energy use data collected from manufacturers, component vendors, reverse engineering, and energy testing. The output of the engineering analysis is the cost-efficiency relationship for each equipment class, which will be used in the life-cycle cost and payback period analyses (chapter 8 of the preliminary TSD) as well as the net present value analysis.

This chapter covers the equipment classes the U.S. Department of Energy (DOE) analyzed and the methodology used by DOE to develop manufacturing costs and energy consumption for the preliminary analysis phase of the rulemaking, as well as the results of these analyses.

During the course of this work, DOE recognized the need to restructure the analyses to consider the cost-effectiveness associated with changing condenser water flow. This issue is discussed in more detail in chapter 2 of the preliminary TSD. The modified analysis structure described in chapter 2 to address this issue will be implemented during the notice of proposed rulemaking (NOPR) phase of the rulemaking, and is not described in detail in this chapter. Additionally, some information obtained prior to publication of this preliminary TSD also is not reflected in this chapter, such as adjustments to the analysis based on discussions with manufacturers. Such additional information will also be incorporated in the analysis during the NOPR phase of the rulemaking.

5.2 EQUIPMENT CLASSES ANALYZED

In the preliminary engineering analysis, DOE directly analyzed 10 of the 22 proposed equipment classes for batch and continuous ice-making machines. This means that DOE developed representative analyses for specific existing products of these equipment classes, conducting energy testing, reverse engineering, and cost-efficiency analyses based on energy use and manufacturing cost models based on the products acquired for reverse engineering. DOE extended the results of the direct analyses to other equipment classes based on similarity of classes.

Table 5.2.1 summarizes the batch ice-making machine equipment classes analyzed in the preliminary engineering analysis and Table 5.2.2 lists the continuous ice-making machine equipment classes analyzed.[a] These equipment classes represent close to 100 percent of the shipments of automatic commercial ice makers. To perform the analysis as efficiently as possible, DOE did not directly analyze all covered equipment classes. DOE extrapolated energy standards to the remaining equipment classes as described in section 5.10. DOE did not conduct full separate analyses for remote condensing unit ice makers with and without remote compressors. DOE considered analyses for the remote condensing unit equipment to be representative of equipment classes both with and without remote compressors. This is discussed in greater detail in section 5.4.1.6.

Table 5.2.1 Batch Equipment Classes Analyzed in the Engineering Analysis

Equipment Type	**Type of Cooling**	**Harvest Capacity Rate** ***lb/24 hours***	**Equipment Class Abbreviation***	**Reverse Engineering Unit, Directly Analyzed Equipment Class**
Ice-Making Head	Water	Small (<500)	IMH-W-Small-B	
		Medium (≥500 and <1,436)	IMH-W-Med-B	✓
		Large (≥1,436)	IMH-W-Large-B	✓
	Air	Small (<450)	IMH-A-Small-B	✓
		Large (≥450)	IMH-A-Large-B	✓
Remote Condensing (but not remote compressor)	Air	Small (<1,000)	RCU-NRC-Small-B	
		Large (≥1,000)	RCU-NRC-Large-B	✓
Remote Condensing and Remote Compressor**	Air	Small (<1,000)	RCU-RC-Small-B	
		Large (≥1,000)	RCU-RC-Large-B	✓
Self-Contained Unit	Water	Small (<200)	SCU-W-Small-B	
		Large (≥200)	SCU-W-Large-B	✓
	Air	Small (<175)	SCU-A-Small-B	✓
		Large (≥175)	SCU-A-Large-B	

* Abbreviation notation: system type (batch (B) or continuous (C)). Equipment type (ice-making head (IMH), remote condenser unit (RCU), self-contained unit (SCU)). Condenser cooling (air (A) or water (W)) or compressor location for RCUs (remote compressor (RC), non-remote compressor (NRC)).

** Includes units designed for connection to a compressor rack system.

---

[a] See chapter 3 of the preliminary TSD for descriptions of batch and continuous ice maker categories.

Table 5.2.2 Continuous Equipment Classes Analyzed in the Engineering Analysis

Equipment Type	Type of Cooling	Harvest Capacity Rate *lb/24 hours*	Equipment Class Abbreviation	Reverse Engineering Unit, Directly Analyzed Equipment Class
Ice-Making Head	Water	Small (<1,000)	IMH-W-Small-C	
		Large (≥1,000)	IMH-W-Large-C	
	Air	Small (<1,000)	IMH-A-Small-C	✓
		Large (≥1,000)	IMH-A-Large-C	
Remote Condensing (but not remote compressor)	Air	Small (<1,000)	RCU-NRC-Small-C	
		Large (≥1,000)	RCU-NRC-Large-C	*
Self-Contained Unit	Water	Small (<175)	SCU-W-Small-C	**
		Large (≥175)	SCU-W-Large-C	
	Air	Small (<175)	SCU-A-Small-C	
		Large (≥175)	SCU-A-Large-C	✓

* DOE acquired a product of this equipment class, but did not complete direct analysis for it for the preliminary analysis.
** DOE was not able to identify any existing products of this equipment class in ice maker databases. Hence, this equipment class was not analyzed, directly or by extrapolation.

5.3 METHODOLOGY OVERVIEW

This section describes the analytical methodology DOE used in the engineering analysis. In this rulemaking, DOE has adopted a combined efficiency level/design option/reverse engineering approach to developing cost-efficiency curves. DOE established efficiency levels defined as percent energy use lower than that of baseline efficiency products. DOE's analysis is based on the efficiency improvements associated with groups of design options. Also, DOE developed manufacturing cost models based heavily on reverse engineering of products to develop a baseline MPC and to support calculation of the incremental costs associated with improvement of efficiency.

Figure 5.3.1 presents the steps in the analysis and illustrates how they contributed to developing the cost-efficiency curves. The process began with data collection and ended with the incremental cost curve results.

To develop the analytically derived cost-efficiency curves, DOE collected information from various sources on the manufacturing cost and energy use reduction characteristics of each of the design options. DOE reviewed product literature, conducted reverse engineering of current products, and interviewed component vendors of compressors and fan motors. DOE also conducted interviews with manufacturers during the preliminary analysis. The engineering questionnaire associated with this discussion is reproduced in appendix 12A.

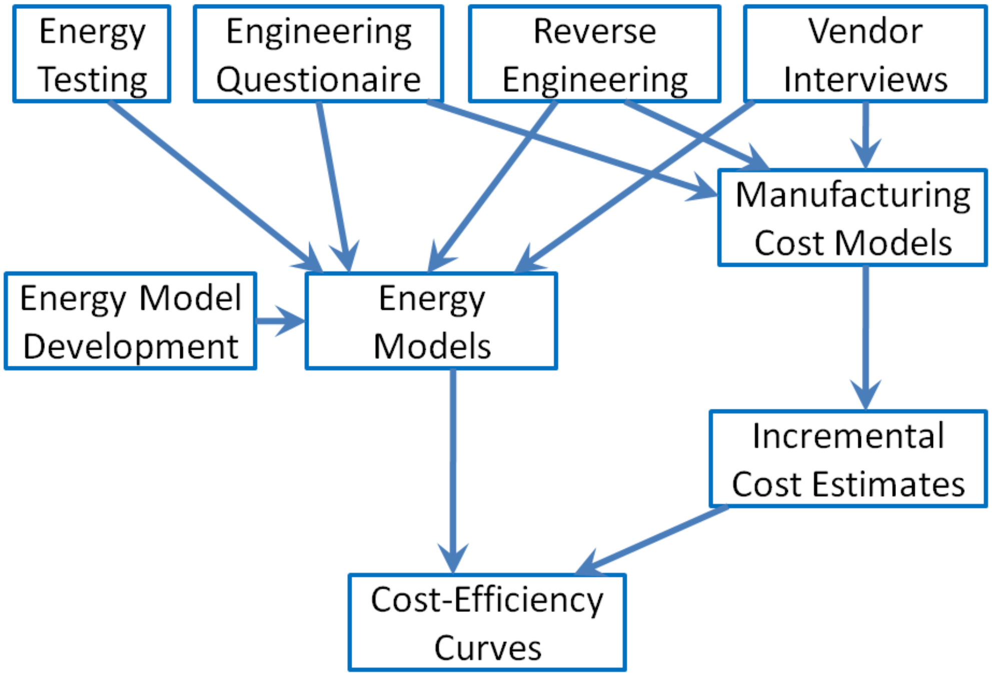

Figure 5.3.1 Flow Diagram of Engineering Analysis Methodology

Cost information from the vendor interviews and engineering questionnaires provided input to the manufacturing cost model. DOE determined incremental costs associated with specific design options both from vendor information and using the cost model. DOE modeled energy use reduction using the FREEZE program, which was developed in the 1990s and upgraded as part of the preliminary analysis. The reverse engineering, vendor interviews, and manufacturer interviews provided input for the energy analysis. The incremental cost estimates and the energy modeling results together constitute the energy efficiency curves presented in this chapter.

5.4 EFFICIENCY LEVELS

5.4.1 Batch Ice Makers

This section discusses the baseline, incremental, and maximum technology efficiency levels that DOE used in its preliminary analysis for automatic commercial ice makers of the batch equipment classes.

5.4.1.1 Baseline: Existing DOE Standards

The Energy Policy and Conservation Act (EPCA), as amended by the Energy Policy Act of 2005, prescribed the following standards for batch ice makers, shown in Table 5.4.1, effective January 1, 2010. 42 U.S.C. 6313(d)(1) These efficiency levels will represent the baseline efficiency levels for batch ice makers. DOE will also adopt these baseline efficiency levels for ice makers with ice harvest capacities of up to 4,000 pounds of ice per 24 hours,[b] except that DOE may adopt a more complicated approach for large air-cooled ice-making head ice makers with harvest capacities larger than 1,600 lb/24 hours. This approach is described in section 5.4.1.4.

Table 5.4.1 Existing DOE Standards for Batch Ice Makers

Equipment Type	**Type of Cooling**	**Harvest Capacity Rate** ***lb/24 hours***	**Maximum Energy Use** ***kWh/100 lb ice****	**Maximum Condenser Water Use***,** ***gal/100 lb ice***
Ice-Making Head	Water	Small (<500)	7.80–0.0055H	200–0.022H
		Medium (≥500 and <1,436)	5.58–0.0011H	200–0.022H
		Large (≥1,436)	4.0	200–0.022H
	Air	Small (<450)	10.26–0.0086H	N/A
		Large (≥450)	6.89–0.0011H	N/A
Remote Condensing (but not remote compressor)	Air	Small (<1,000)	8.85–0.0038H	N/A
		Large (≥1,000)	5.1	N/A
Remote Condensing and Remote Compressor	Air	Small (<934)	8.85–0.0038H	N/A
		Large (≥934)	5.3	N/A
Self-Contained Unit	Water	Small (<200)	11. 40–0.019H	191–0.0315H
		Large (≥200)	7.6	191–0.0315H
	Air	Small (<175)	18.0–0.0469H	N/A
		Large (≥175)	9.8	N/A

kWh = kilowatt-hours.
* H = Harvest rate in pounds per 24 hours.
** Water use is for the condenser only and does not include potable water used to make ice.

5.4.1.2 Maximum Available Efficiency Levels

Maximum available efficiency levels for the analyzed equipment classes are tabulated in Table 5.4.2. This information is based on a survey of product databases and manufacturer websites (also see data in chapter 3 of the preliminary TSD). The maximum available efficiency levels are represented by percentage energy use less than the energy use of baseline-efficiency equipment, which has been selected as equal to the current DOE energy standard for batch ice makers. DOE used the maximum available efficiency levels to select appropriate ranges of incremental efficiency levels.

---

[b] For brevity, pounds of ice per 24 hours will be referred to herein as lb/24 hours.

Table 5.4.2 Batch Ice Maker Maximum Available Levels

Equipment Type	Type of Cooling	Harvest Capacity Rate *lb/24 hours*	Max Available Efficiency Level*	Harvest Capacity *lb/24 hours*	Brand & Model Number
Ice-Making Head	Water	Small (<500)	25%	382	Hoshizaki KMD-410MWH
		Medium (≥500 and <1,436)	22%	662 1,323	Hoshizaki KM-650MWH, KM-1301SWH
		Large (≥1,436)	23%	1,850	Hoshizaki KM-1900SWH
	Air	Small (<450)	24%	280	Scotsman C0330MA-1#, -32#
		Large (≥450)	21%	1,530	Hoshizaki KM-1900SAH
Remote Condensing (but not remote compressor)	Air	Small (<1,000)	20%	554, 589 780	Hoshizaki KM-650MRH, KML-631MRH Scotsman C0830MR-3#, -32#
		Large (≥1,000)	27%	1,675	Hoshizaki KMH-2000SRH3
Remote Condensing and Remote Compressor	Air	Small (<934)	12%	800	Manitowoc SD-1072C
		Large (≥934)	15%	1,500 1,550 1,235	Manitowoc SD-1872C, Manitowoc SY-1874C, Manitowoc SY-1474C
Self-Contained Unit	Water	Small (<200)	25%	186	Hoshizaki KM-201BWH
		Large (≥200)	28%**	439	Hoshizaki DKM-500BWH
	Air	Small (<175)	32%	55	Hoshizaki AM-50BAE
		Large (≥175)	31%	406	Hoshizaki DKM-500BAH

* Percent energy use lower than the baseline efficiency level (*i.e.*, the current DOE standard).

** Maximum available for under-counter model.

5.4.1.3 Incremental Efficiency Levels

For each of the 13 analyzed batch ice equipment classes, DOE established a series of incremental efficiency levels, for which it has developed incremental cost data and quantified the cost-efficiency relationship. DOE established the highest incremental efficiency levels based on a review of the maximum efficiency levels of available products, as discussed in section 5.4.1.2. Table 5.4.3 shows the selected incremental efficiency levels.

Table 5.4.3 Incremental Efficiency Levels for Batch Ice Maker Equipment Classes

Equipment Type*	Harvest Capacity Rate *lb/24 hours*	EL2**	EL3	EL4	EL5	EL6
IMH-W-Small-B	Small (<500)	10%	15%	20%		
IMH-W-Med-B	Medium (≥500 and <1,436)	10%	15%	20%		
IMH-W-Large-B	Large (≥1,436)	10%	15%	20%		
IMH-A-Small-B	Small (<450)	10% (E-STAR)	15%	20%		
IMH-A-Large-B	Large (≥450 and <1,600)	10% (E-STAR)	15%	20%		
IMH-A-E-B	Extended (≥1,600)	See section 5.4.1.4				
RCU-NRC-Small-B	Small (<1,000)	9% (E-STAR)	15%	20%	25%	
RCU-NRC-Large-B	Large (≥1,000)	9% (E-STAR)	15%	20%	25%	
RCU-RC-B	Small (<934)	9% (E-STAR)	15%			
	Large (≥934)	9% (E-STAR)	15%			
SCU-W-Small-B	Small (<200)	7%	15%	20%	25%	
SCU-W-Large-B	Large (≥200)	7%	15%	20%	25%	
SCU-A-Small-B	Small (<175)	7% (E-STAR)	15%	20%	25%	30%
SCU-A-Large-B	Large (≥175)	7% (E-STAR)	15%	20%	25%	30%

* See Table 5.2.1 for a description of these abbreviations.
** EL = efficiency level; EL1 is the base line efficiency level, while EL2 through EL6 represent increased efficiency levels.

5.4.1.4 Efficiency Levels for Extended Harvest Capacity Air-Cooled Ice-Making Head Batch Ice Makers

The current DOE energy conservation standard for large air-cooled ice-making head batch ice makers decreases with harvest capacity well beyond the harvest capacity of existing products. At the current maximum harvest capacity for this equipment class, the standard may not be practical to achieve. When the harvest capacity range for ice makers extends to 4,000 lb/24 hours, this issue would be further exacerbated. Even though no ice makers of this equipment class are currently produced in this capacity range, DOE is considering adopting incremental efficiency levels in the analysis for this equipment class that do not further exacerbate this issue. The incremental efficiency levels would, to the extent possible, level out the standard so that it is independent of harvest capacity, as is the case for all other high harvest capacity equipment classes. The leveling of the standard is subject to the EPCA anti-backsliding provisions; so for some part of the harvest capacity range, some of the incremental efficiency levels are equal to the current standard.

This is illustrated in Figure 5.4.1 for Efficiency Level 2, which follows the current ENERGY STAR® requirement up to 1,600 lb/24 hours harvest capacity, after which it levels out, except for the range of harvest capacity for which it must follow the current DOE standard to avoid backsliding. Efficiency Level 3 would be constructed similarly, leveling out at 1,600 lb/24 hours and 4.4 kWh/100 lb and intersecting the existing standard line at a harvest capacity of

2,260 lb/24 hours. Efficiency Level 4 would level out at 1,600 lb/24 hours and 4.1 kWh/100 lb and would remain at this level up to 4,000 lb/24 hours. DOE realizes that adopting incremental efficiency levels as described may not impact any existing products, and that very few, if any, products may fall in this harvest capacity range in the future. However, this approach will avoid adopting unreasonably stringent standards for this harvest capacity range as part of this rulemaking. The capacity range above 1,600 lb/24 hours has been designated the "extended" range to distinguish it from the current "large" class of the current energy standards.

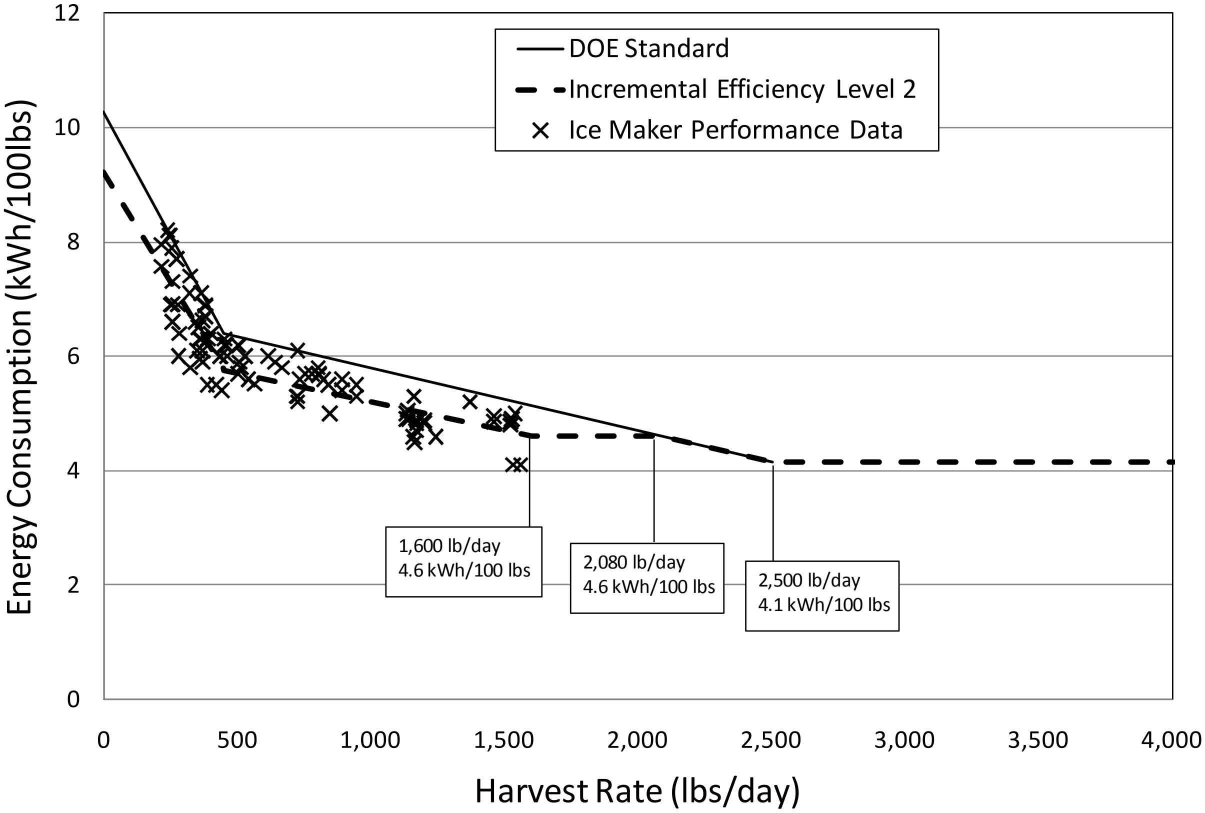

Figure 5.4.1 Incremental Efficiency Levels for Extended Harvest Capacity Air-Cooled Ice-Making Head Ice Makers

5.4.1.5 Maximum Technology Level

DOE defines maximum technology levels for each equipment class to represent the maximum possible efficiency if all available design options are incorporated. The maximum technology level is not necessarily the same as the maximum available level, which is the highest efficiency unit currently available on the market. In some cases, the maximum technology level is not commercially available because it is not economically feasible. In other cases, the maximum available efficiency products use design options that have been screened out because they may be proprietary and/or because they may reduce equipment utility (*e.g.*, larger physical size in order to allow use of larger heat exchangers).

DOE determined maximum technology levels using energy modeling. The energy models for the maximum technology levels were based on use of all design options applicable for the specific equipment classes. The maximum technology efficiency levels for the analyzed batch ice maker equipment classes are presented in Table 5.4.4. The design options considered in the analysis are listed for each equipment class in section 5.9.

For some equipment classes, the table shows two maximum technology levels. For these cases, the two levels are representative of analyses conducted for two very different harvest capacities.

Also, the table does not show maximum technology levels separately for remote condenser units with and without remote compressors. DOE did not consider remote compressor and non-remote compressor units separately in the analysis. This is discussed in more detail in section 5.4.1.6.

Table 5.4.4 Maximum Technology Levels for Batch Ice Maker Equipment Classes

Equipment Class	Energy Use Lower than Baseline
IMH-W-Small-B	14%
IMH-W-Med-B	10%
IMH-W-Large-B	11% (at 1,500 lb/24 hours) 3% (at 2,600 lb/24 hours)
IMH-A-Small-B	20%
IMH-A-Large-B	20% (at 800 lb/24 hours) 15% (at 1,500 lb/24 hours)
RCU-Small-B	16.5%
RCU-Large-B	16.5% (at 1,500 lb/24 hours) 14% (at 2,400 lb/24 hours)
SCU-W-Small-B	24%
SCU-W-Large-B	39%
SCU-A-Small-B	28%
SCU-A-Large-B	25%

5.4.1.6 Efficiency Levels for Remote Condensing Unit Ice Makers

Remote condensing unit ice makers may have compressors in the same package as the evaporator, or their compressors may be housed with the condenser. The latter approach is used to remove from the interior space the noise associated with the compressor, which can be a distinct market advantage in some applications. Moving the compressor to the condenser package of a remote condenser ice maker (with a remote compressor) adds complexity to the refrigeration system design, particular for batch ice makers, in which the refrigeration system alternates between freeze and harvest cycles. Remote compressor units also have significantly longer suction lines, since the compressor is no longer in the same equipment package as the evaporator. Interconnecting refrigerant line sets can be as long as 100 feet or more. However, Air-Conditioning, Heating, and Refrigeration Institute (AHRI) Standard 810-2007 requires testing with line sets that are at least 25 feet long. It is well known that pressure drop in the suction line can reduce the efficiency of refrigeration systems because refrigerant pressure at the compressor inlet is lower. The system efficiency can also be affected by heat gain to the refrigerant in the suction line, although this effect is mitigated in most ice makers through the use of insulation and suction line heat exchangers located near the evaporators.

The existing DOE energy conservation standards for large harvest capacity remote condenser cube ice makers take into account the potential losses associated with the suction line of remote compressor units. The standard for ice makers with remote compressors is 5.3 kWh/100 lb, as compared with 5.1 kWh/100 lb for remote condenser ice makers without remote compressors (see Table 5.4.1).

DOE considered whether separate equipment classes for remote condenser ice makers are justified and whether the costs required to achieve higher efficiency levels would be higher for remote compressor equipment than they are for non-remote compressor equipment.

DOE calculated suction line pressure drop and its expected impact on compressor efficiency during the freeze cycle for two large-harvest-capacity batch ice makers, using compressor performance data for the compressors used in these products. Based on discussions with manufacturers and ice maker test data, DOE selected representative operating conditions for this analysis, reviewing the impact of the suction line pressure drop for evaporating temperatures of 20 °F and 10 °F, because the batch ice maker evaporating temperature varies as ice builds up on the evaporator. The analysis, summarized in Table 5.4.5, shows that the 0.2 kWh/100 lb differential of the current DOE standard is appropriate for the two types of remote condenser ice makers.

Table 5.4.5 Impact of Suction Line Pressure Drop for Remote Compressor Ice Makers*

	Ice Maker 1		**Ice Maker 2**	
Harvest Capacity (lb/24 hours)	1,500		2,400	
Suction Line Description	One ¾ inch OD line		Two ¾ inch OD lines	
Evaporating Temperature (°F)	10	20	10	20
Suction Temperature (°F)	50	55	50	55
Suction Line Pressure Drop (psi)	2.6	3.6	1.3	1.6
Increase in Energy Use (kWh/100 lb)	0.22	0.26	0.08	0.09

OD = outer diameter.

* Condensing temperature 110 °F

DOE considered whether the efficiency improvements associated with the design options used in the engineering analysis would be significantly different for remote compressor ice makers as compared with non-remote compressor models. DOE concluded that there would be few differences in the magnitudes or costs of these improvements as the design options are applied to these two types of ice makers. Hence, DOE considered that the relationship between incremental cost and efficiency for one of the types would provide an accurate representation of this trend for the other type. Consequently, the results for RCU ice makers are not separately presented for remote compressor and non-remote compressor ice makers, and they are representative of both types. The percent reductions associated with the efficiency levels would be applied to the 5.1 and 5.3 kWh/100 lb baseline energy use levels of the large-harvest-capacity remote condenser ice makers to determine the energy use associated with the efficiency level. For instance, the 9 percent Efficiency Level 1 (equivalent to ENERGY STAR) for these ice makers would represent 4.6 kWh/100 lb for non-remote compressor ice makers and 4.8 kWh/100 lb for remote compressor units.

5.4.2 Continuous Ice Makers

5.4.2.1 Energy Use Metric Incorporating Ice Hardness

Continuous type ice makers typically produce ice that is not completely frozen, leaving some liquid water content in the total mass of ice produced. The ice hardness (for a 32 °F ice product, the percentage of frozen ice) is directly related to the measured energy consumption of these machines. To account for this impact on energy use, the DOE test procedure final rule requires that the measured energy use of continuous machines be adjusted based on the ice hardness. 77 FR 1591, 1597 (Jan. 11, 2012).

The new test procedure calls for use of a calorimeter to determine ice hardness, and calculation of an ice hardness adjustment factor based on the calorimeter test results as follows:

$$\text{Ice Hardness Adjustment Factor} = \left[\frac{144\,{}^{\text{Btu}}/_{\text{lb}} + 38\,{}^{\text{Btu}}/_{\text{lb}}}{144\,{}^{\text{Btu}}/_{\text{lb}} \times \left({}^{\text{Ice Hardness Factor}}/_{100}\right) + 38\,{}^{\text{Btu}}/_{\text{lb}}}\right]$$

The measured energy consumption per 100 lb of ice and the measured condenser water consumption, as determined using American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) Standard 29-2009, are multiplied by the ice hardness adjustment factor to yield the adjusted energy and condenser water consumption values, respectively.

DOE's consideration of continuous ice maker efficiency levels and its rulemaking analysis in general are based on use of the adjusted energy and condenser use values.

5.4.2.2 Baseline Efficiency Levels

Currently there are no DOE energy standards for continuous ice makers. The Framework document and Framework public meeting presentation discussed two options for development of baseline efficiency levels:

1. Use of the Canadian standard levels.

2. Development of efficiency levels based on examination of the ice maker energy use data and fitting of baseline efficiency level curves to the data to represent the relationship of energy use as a function of harvest capacity.

DOE chose to develop efficiency levels based on the ice maker data because (a) the Canadian standard levels do not take into consideration the adjustment of measured energy use as a function of ice hardness and (b) the Canadian standard levels do not consider differences in equipment type (*i.e.*, ice-making head, remote condenser unit, or self-contained unit).

DOE developed baseline efficiency levels using energy use data available from several sources, as discussed in chapter 3 of the preliminary TSD. DOE chose baseline efficiency levels that would be met by nearly all ice makers represented in the databases. These baselines are preliminarily referred to as "trial baselines"—DOE may consider alternative baseline efficiency levels depending on comments from interested parties and on the availability of additional data. Also, because data regarding ice hardness were not available, DOE used assumptions of 0.7 ice hardness for flake ice makers and 0.85 for nugget ice makers to adjust the energy use data. Adjustment of the baseline efficiency levels may be warranted later if many ice makers exhibit ice hardness significantly different from these levels. DOE selected harvest capacity break points (harvest capacities at which the slopes of the trial baseline efficiency levels change) for all but the self-contained equipment classes consistent with those selected by the Consortium for Energy Efficiency (CEE) for their new Tier 2 efficiency level for flake ice makers.[1] Note that DOE did not also adopt the CEE energy use levels for any of its incremental efficiency levels because the CEE energy use levels do not incorporate adjustment of the measured energy use based on ice hardness.

The baseline efficiency levels are tabulated in Table 5.4.6, and they are plotted with the ice maker energy use data in chapter 3 of the preliminary TSD. Note that the remote condensing equipment classes have not been separated into remote compressor and non-remote compressor classes. This is because the available data provide little evidence that the energy use of remote compressor continuous ice makers is higher than that of non-remote compressor ice makers.

Table 5.4.6 Trial Baseline Efficiency Levels for Continuous Ice Maker Equipment Classes

Equipment Type	**Type of Cooling**	**Harvest Capacity Rate** *lb/24 hours*	**Energy Use** *kWh/100 lb ice**
Ice-Making Head	Water	Small (<1,000)	8.1–0.003H
		Large (≥1,000)	5.1
	Air	Small (<1,000)	10.3–0.004H
		Large (≥1,000)	6.3
Remote Condensing	Air	Small (<1,000)	9.5–0.004H
		Large (≥1,000)	5.5
Self-Contained Unit	Water	Small (<175)	9.5–0.0183H
		Large (≥175)	6.3
	Air	Small (<175)	18.0–0.0469H
		Large (≥175)	9.8

* H = Harvest capacity in lb/24 hours

5.4.2.3 Maximum Available Efficiency Levels

Maximum available efficiency levels for the analyzed equipment classes are tabulated in Table 5.4.7. This information is based on a survey of product databases and manufacturer websites (also see data in chapter 3 of the preliminary TSD). The maximum available efficiency levels are represented by percentage energy use less than the energy use of baseline-efficiency equipment. DOE used the maximum available efficiency levels to select appropriate ranges of incremental efficiency levels.

Table 5.4.7 Continuous Ice Maker Maximum Available Efficiency Levels

Equipment Type	Type of Cooling	Harvest Capacity Range	Max Available Efficiency level	Harvest Capacity *lb/24 hours*	Brand & Model Number
Ice-Making Head	Water	Small	35%	877	Ice-O-Matic GEM0956W
		Large	20%	1,040	Scotsman F1222W
	Air	Small	37%	753	Ice-O-Matic GEM0956A
		Large	32%	2,000 1,800	Ice-O-Matic MFI2400 Scotsman FME2404AS
Remote Condensing (but not remote compressor)	Air	Small	26%	835	Scotsman N0922R
		Large	42%	1,780	Scotsman FME2404RS
Remote Condensing and Remote Compressor	Air	All Capacities	9%	771	Follett HCC1000R***
Remote Condenser and Compressor Rack	Air	All Capacities	88%	1,730	Hoshizaki F-2000MLH(-C)
Self-Contained Unit	Water	Small	None		
		Large	15%	495	Hoshizaki DCM-500BWH
	Air	Small	11%	64	Hoshizaki C-100BAE-AD
		Large	39%	403	Ice-O-Matic EF800A**S

Note: This information is based on data available prior to the recent posting on AHRI's website of ratings for continuous machines.

5.4.2.4 Incremental Efficiency Levels

For each of the 10 analyzed continuous ice maker equipment classes, DOE established a series of incremental efficiency levels, for which it has developed incremental cost data and quantified the cost-efficiency relationship. DOE established the highest incremental efficiency levels based on a review of the maximum efficiency levels of available equipment, as discussed in section 5.4.2.3. Table 5.4.8 shows the selected incremental efficiency levels. The efficiency levels are defined by the percent energy use less than the trial baseline energy use, or other energy use levels as indicated in the table.

DOE selected the efficiency levels for the RCU and SCU continuous ice makers to match efficiency levels of batch ice makers. This potentially will allow some of these batch and continuous ice maker equipment classes to be combined, if the cost-effective efficiency levels are the same for both types of equipment. This approach was not feasible for the ice-making head equipment classes because of the very different capacities at which the efficiency level slopes change for batch and continuous ice makers of these types.

Table 5.4.8 Incremental Efficiency Levels for Continuous Ice Maker Equipment Classes

Equipment Type*	Harvest Capacity *lb/24 hours*	EL2**	EL3	EL4	EL5	EL6
IMH-W-Small-C	<1,000	10%	15%	20%	25%	30%
IMH-W-Large-C	≥1,000					
IMH-A-Small-C	<1,000	10%	15%	20%	25%	30%
IMH-A-Large-C	≥1,000					
RCU-Small-C	<1,000	batch baseline	10% less than EL1	15% less than EL1	20% less than EL1	25% less than EL1
RCU-Large-C	≥1,000	7%	17%	21%	26%	30%
SCU-W-Small-C	<175	20% less than batch baseline	25% less than batch baseline	30% less than batch baseline		
SCU-W-Large-C	≥175	3%	10%	16%		
SCU-A-Small-C	<175	7%	15%	20%	25%	
SCU-A-Large-C	≥175	7%	15%	20%	25%	30%

* See Table 5.2.2 for a description of these abbreviations.
** EL = efficiency level; EL1 is the base line efficiency level while EL2 through EL6 represent increased efficiency levels.

5.4.2.5 Maximum Technology Level

The maximum technology efficiency levels for the analyzed batch ice maker equipment classes are presented in Table 5.4.9. The design options considered in the analysis are listed for each equipment class in section 5.9.

For one equipment class, the table shows two maximum technology levels. For these cases, the two levels are representative of analyses conducted for two very different harvest capacities.

For another equipment class, SCU-W-Small-C, the table shows no maximum technology efficiency level. Ice maker databases indicated that there is no equipment in this class. Hence, DOE did not conduct analysis of this equipment class. DOE expects to set energy standards for this equipment class at the level indicated in Table 5.4.8 that ensures continuity with the standards for the SCU-W-Large-C class.

Table 5.4.9 Maximum Technology Levels for Continuous Ice Maker Equipment Classes

Equipment Class	Energy Use Lower than Baseline
IMH-W-Small-C	33%
IMH-W-Large-C	24%
IMH-A-Small-C	30% (at 310 lb/24 hours) 42% (at 820 lb/24 hours)
IMH-A-Large-C	35%
RCU-NRC-Small-C	16.5%
RCU-NRC-Large-C	16.5%
SCU-W-Small-C	*
SCU-W-Large-C	18%
SCU-A-Small-C	18%
SCU-A-Large-C	36%

* DOE was not able to identify any products of this equipment class in ice maker databases. Hence, DOE did not conduct analysis to determine maximum technology level for this class.

5.5 DATA COLLECTION

5.5.1 Component Vendor Data

DOE contacted major suppliers of key commercial ice maker components to obtain performance and cost data to support its design option analysis. This effort consisted of phone interviews and email correspondence. Table 5.5.1 lists the vendors contacted.

DOE also obtained from the compressor vendors or their websites complete performance data for compressors used in the energy analyses, including analyses for baseline and improved-efficiency configurations.

Table 5.5.1 Component Vendors Contacted by DOE during Engineering Analysis

Component Type	Vendors
Compressors	Bristol Copeland Danfoss Embraco Tecumseh
Condenser Fan Motors	A.O. Smith Bohn EBM Papst Emerson Climate Technologies Fasco Marathon Electric Morrill Motors Regal Beloit Electric Motors Zhongshan Broad Ocean Motors
Auger Motors	Brother International Emerson Industrial Automation Bison Gear Motors
Pump Motors	Fasco Hartell Morrill Motors Sanso Electric

5.5.2 Reverse Engineering

DOE purchased a number of representative automatic commercial ice makers as part of the engineering analysis in order to examine design and fabrication details. This reverse engineering included detailed measurement of dimensions, system and component-level power measurements, measurement of air flows for products with forced convection heat exchangers, and physical teardowns. The results of the reverse engineering process were used as input to the manufacturing cost modeling and the energy use modeling. This section describes the selection of products for reverse engineering as well as some of the measurements made to support subsequent modeling. Section 5.6 more thoroughly describes the physical teardown process used to support manufacturing cost modeling.

5.5.2.1 Selection of Products for Reverse Engineering

Table 5.5.2 describes the products selected for reverse engineering and identifies the products for which DOE conducted energy tests (see section 5.5.4 for more on energy testing). DOE aimed to select a range of models that would cover a broad spectrum of equipment classes and capacities based on the CEC, ENERGY STAR, and AHRI databases, as well as manufacturer websites.

Table 5.5.2 Selected Units for Reverse-Engineering and Energy Testing

Type	Equipment Class	Harvest Capacity *lb/24 hours*	Energy Use *kWh/ 100 lb*	Potable Water Use *gal/100 lb*	Energy Test	Physical Tear-down	Energy Use Model
Batch	IMH-A-Small-B	270	7.70	20.0	✓	✓	✓
	IMH-A-Small-B	324	5.80	22.6	✓	✓	✓
	IMH-A-Large-B	780	5.70	20.5		✓	✓
	IMH-A-Large-B	844	5.00	18.4		✓	✓
	IMH-A-Large-B	1,460	4.95	20.0		✓	✓
	IMH-A-Large-B	1,560	4.10	18.8	✓	✓	✓
	IMH-W-Large-B	851	4.40	19.7		✓	✓
	IMH-W-Large-B	2,820	3.60	19.7	✓	✓	✓
	RCU-A-Large-B	1,510	4.59	20.0		✓	✓
	RCU-A-Large-B	1,694	3.80	18.1	✓	✓	✓
	RCU-A-Large-B	2,350	4.64	19.7		✓	✓
	SCU-A-Small-B	121	8.40	17.8	✓	✓	✓
	SCU-A-Small-B	112	11.80	34.0		✓	✓
	SCU-W-Large-B	285	5.50	18.0	✓	✓	✓
Continuous	IMH-A-Small-C	310	6.31	12.0		✓	✓
	IMH-A-Small-C	822	5.51	13.6		✓	✓
	IMH-A-Small-C	845	3.40	12.0	✓	✓	✓
	RCU-A-Large-C	1780	3.40	12.0	✓	✓	✓
	SCU-A-Large-C	280	6.00	19.0	✓	✓	✓

5.5.2.2 Collection of Energy Modeling Data

DOE examined each unit prior to teardown to record details to be used as input for the energy modeling. The key measurements are described in this section.

The rated capacity and energy use for each product were based on the AHRI database or on product literature.

DOE contracted with Intertek Testing Services, Inc. (Intertek) in Cortland, New York for testing. The test laboratory measured the harvest capacity and energy use of the tested ice makers in accordance with AHRI Standard 810-2007. For batch ice makers with multiple purge water settings, Intertek tested the units in both the "standard" purge water setting and the highest purge water setting to evaluate the water use and energy use impacts of adjusting the purge water quantity. Only one of the tested ice makers had adjustable purge water control. DOE also had Intertek conduct calorimeter tests for the continuous ice makers that were tested, and bin effectiveness tests in accordance with AHRI Standard 820-2000, *Standard for Ice Storage Bins,* for the self-contained units that were tested.

DOE measured component-level power input for fans, water pumps, and air pumps for the products that had these components. For some of the continuous ice makers, DOE measured augur motor power input while the ice maker was making ice. In some cases, DOE also measured the energy use associated with solenoid valves and the control boards.

DOE made air flow measurements for all air-cooled condensers using a hot wire anemometer. The location of these measurements varied depending on the heat exchanger type and configuration. The determination of air flows based on these measurements is not very reliable, so this measurement was used as an indication of air flow trends more than an exact indication of air flow for the various products.

Details of the cabinet size, heat exchanger dimensions, insulation thickness, etc. were based on direct physical measurements, made during the teardown process. DOE noted condenser details including type, configuration, numbers of tubes and fins, dimensions, etc. The details of evaporators and suction line heat exchangers were similarly determined during teardown.

DOE recorded component manufacturer and model data for key components such as compressors, fans, and controls.

5.5.3 Manufacturer Interviews

DOE's contractor discussed engineering issues with manufacturers during the preliminary analysis interviews. The engineering questions were consolidated into an engineering questionnaire, which guided the interview process for all of these discussions. The engineering questionnaire is shown in appendix 12A. Key technical topics addressed during these discussions include the following:

- Typical characteristics of components and typical design details (*i.e.*, evaporator configuration) used for key equipment classes
- Typical design differences between baseline and ENERGY STAR products
- Differences in design pathways and incremental costs across different equipment classes
- Viability of technology options and their typical costs

All of these interviews were conducted under non-disclosure agreements with the manufacturers. Hence, none of the individual responses can be reported. However, values for many of the parameters and costs used in the engineering analysis were based on aggregated input from these discussions.

5.5.4 Energy Testing

DOE conducted energy testing to verify energy use of several of the ice makers obtained for reverse engineering, and to provide information about refrigeration system operating conditions during different phases of operation to support energy use modeling. Ten ice makers were tested, as indicated in Table 5.5.2. During the tests, the following data were recorded:

- Potable water use
- Refrigeration circuit temperatures
- Refrigerant pressures
- Potable water circuit temperatures
- Air temperatures, including the evaporator compartment, compressor/condenser compartment, condenser fan air outlet (for air-cooled and remote air-cooled machines)
- Cooling water inlet and outlet temperatures
- Machine power input raw data and accumulated energy use

5.6 MANUFACTURING COST MODELING

5.6.1 Generation of Bills of Materials

Each teardown resulted in a structured bill of materials (BOM). Structured BOMs describe each product part and its relationship to the other parts in the estimated order in which manufacturers assembled them. The BOMs describe each fabrication and assembly operation in detail, including the type of equipment needed (*e.g.*, presses, drills), the process cycle times, and the labor associated with each manufacturing step. The result is a thorough and explicit model of the production process, which includes space, conveyor, and equipment requirements by planned production level.

The BOMs incorporate all materials, components, and fasteners classified as either raw materials or purchased parts and assemblies. The classifications into raw materials or purchased parts were based on DOE's previous industry experience, recent information in trade publications, and discussions with high- and low-volume original equipment manufacturers (OEMs). DOE also visited manufacturing plants to reinforce its understanding of the industry's current manufacturing practices.

For purchased parts, the purchase price is estimated based on volume-variable price quotations and detailed discussions with manufacturers and component suppliers. For fabricated parts, the prices of "raw" metals (*e.g.*, tube, sheet metal) are estimated based on 5-year averages (see section 5.6.4.3), while all other materials and purchased parts reflect current market costs. The cost of transforming the intermediate materials into finished parts is estimated based on current industry pricing.

5.6.2 Cost Structure of the Spreadsheet Models

The manufacturing cost assessment methodology used is a detailed, component-focused technique for calculating the manufacturing cost of a product (direct materials, direct labor, and the overhead costs associated with production). The first step in the manufacturing cost assessment was the creation of a complete and structured BOM from the disassembly of the units selected for teardown. The units were dismantled, and each part was characterized according to weight, manufacturing processes used, dimensions, material, and quantity. The BOM incorporated all materials, components, and fasteners with estimates of raw material costs and purchased part costs. Assumptions about the sourcing of parts and in-house fabrication were based on industry experience, information in trade publications, and discussions with manufacturers. Interview and plant visits were conducted with manufacturers to add industry experience on the methodology and pricing.

The last step was to convert this information into dollar values. To perform this task, DOE collected information on labor rates, tooling costs, raw material prices, and other factors. DOE assumed values for these parameters using internal expertise and confidential information available to DOE contractors. Although most of the assumptions are manufacturer specific and cannot be revealed, section 5.6.4.2 discusses the values used for each assumption.

In summary, DOE assigned costs of labor, materials, and overhead to each part, whether purchased or produced in-house. DOE then aggregated single-part costs into major assemblies (*e.g.*, heat exchanger assembly, potable water system, packaging, controls, fan/motor assembly, refrigerant circuit, wiring harnesses) and summarized these costs in a worksheet.

5.6.3 Cost Model and Definitions

Once DOE disassembled selected units, gathered information from manufacturer catalogs on additional products, and identified technologies, DOE created an appropriate manufacturing cost model that could translate physical information into MPCs. The cost model is based on production activities and divides factory costs into the following categories:

- Materials: Purchased parts (*i.e.*, compressor, fan motors, control boards, etc.), raw materials (*i.e.*, cold rolled steel, copper tube, etc.), and indirect materials that are used for processing and fabrication.
- Labor: Fabrication, assembly, indirect, and supervisor labor. Fabrication and assembly labor costs are burdened with benefits and supervisory costs.
- Overhead: Equipment, tooling, and building depreciation, as well as utilities, equipment and tooling maintenance, insurance, and property taxes.

5.6.3.1 Cost Definitions

Because there are many different accounting systems and methods to monitor costs, DOE defined the above terms as follows:

- Direct material: Purchased parts (out-sourced) plus manufactured parts (made in-house from raw materials).
- Indirect material: Material used during manufacturing (*e.g.*, welding rods, adhesives).
- Fabrication labor: Labor associated with in-house piece manufacturing.
- Assembly labor: Labor associated with final assembly.
- Indirect labor: Labor costs that scaled with fabrication and assembly labor. This included the cost of technicians, manufacturing engineering support, stocking, etc. that were assigned on a span basis.
- Equipment and plant depreciation: Money allocated to pay for initial equipment installation and replacement as the production equipment wears out.
- Tooling depreciation: Cost for initial tooling (including nonrecurring engineering and debugging of the tools) and tooling replacement as tools wear out.
- Building depreciation: Money allocated to pay for the building space and the conveyors that feed and/or make up the assembly line.
- Utilities: Electricity, gas, telephones, etc.
- Maintenance: Money spent annually on maintaining tooling and equipment.
- Insurance: Appropriated as a function of unit cost.
- Property Tax: Appropriated as a function of unit cost.

5.6.4 Cost Model Assumptions Overview

As discussed in the previous section, assumptions about manufacturer practices and cost structure were important to the final product cost estimate.

In converting physical information about the product into cost information, DOE reconstructed manufacturing processes for each component using internal expertise and knowledge of the methods used by the industry. DOE used assumptions regarding the manufacturing process parameters (*e.g.*, equipment use, labor rates, tooling depreciation, and cost of purchased raw materials) to determine the value of each component. DOE then summed the values of the components into assembly costs and, finally, the total product cost. The product cost included the material, labor, and overhead costs associated with the manufacturing facility. The material costs included both direct and indirect materials. The labor costs included assembly, fabrication, supervisor, and indirect labor. Overhead costs included equipment depreciation, tooling depreciation, building depreciation, utilities, equipment, tooling maintenance, insurance, property, and taxes.

DOE used the information gathered from manufacturer interviews and factory visits to help in development of the cost model.

The following sections discuss specific assumptions about outsourcing, factory parameters, production volumes, and material prices. Manufacturer-specific assumptions are presented as industry averages to prevent disclosure of confidential information.

5.6.4.1 Fabrication Estimates

DOE characterized parts based on whether manufacturers purchased them from outside suppliers or fabricated them in-house. For purchased parts, DOE estimated the purchase price. For fabricated parts, DOE estimated the price of raw materials (*e.g.*, tube, sheet metal) and the cost of transforming them into finished parts. Whenever possible, DOE obtained price quotes directly from the manufacturers' suppliers.

DOE based the manufacturing operations assumptions on internal expertise, interviews with manufacturers, and manufacturing facilities site visits. The major manufacturer processes identified and developed for the spreadsheet model are listed in Table 5.6.1. Fabrication process cycle times were estimated and entered into the BOM.

Table 5.6.1 Cost Model In-House Manufacturing Operation Assumptions

Fabrication	Finishing	Assembly/Joining	Quality Control
Fixturing Stamping/Pressing Turret Punch Tube Forming Machine Cutting & Shearing T-Drill Tube/Wire Bending Brazing Vacuum Forming Blow Molding	Washing Painting Powder Coating De-burring Polishing Refrigerant Charging	Adhesive Bonding Spot Welding Seam Welding Packaging	Inspecting & Testing

5.6.4.2 Factory Parameters Assumptions

DOE used information gathered from publicly available literature, manufacturer interviews, and analysis of common industry practices to formulate factory parameters for each type of manufacturer. DOE first made assumptions about a set of preliminary factory parameters before the manufacturer interviews. DOE then revised the assumptions using comments and information gathered during the interviews. Table 5.6.2 lists DOE's assumptions for ice maker manufacturers.

Table 5.6.2 ACIM Factory Parameter Assumptions

Parameter	Batch	Continuous
Plant Capacity (units/yr)	25,000	6,000
Actual Annual Production Volume (units/yr)	12,000	3,000
Fabrication Labor Wages ($/hr)	16.00	16.00
Fringe Benefits Ratio	50%	50%

5.6.4.3 Material Cost Assumptions

DOE determined the cost of raw materials using publicly available information such as the American Metals Market,[2] interviews with manufacturers, and direct discussions with material suppliers. Common metals used in the fabrication of ice makers include cold rolled steel, stainless steel, copper tubing, and aluminum. There have been large fluctuations in metal prices over the last few years. To account for these fluctuations, DOE used a 5-year average of metal prices from the Bureau of Labor Statistics Producer Price Indices (PPIs) spanning from 2006 to 2011 with an adjustment to 2011 dollars (2011$).[3] DOE used the PPIs for copper rolling, drawing, and extruding and steel mill products, and made the adjustments to 2011$ using the gross domestic product implicit price deflator.[4] For resins used in the fabrication of these refrigeration products, DOE used current resin prices gathered from industry research, publications such as Plastics News,[5] and interviews with manufacturers.

5.6.5 Manufacturing Production Cost

After finalizing the cost estimate for each teardown unit, DOE prepared a detailed summary for relevant components, subassemblies, and processes. The BOM thus details all aspects of product costs. DOE totaled the cost of materials, labor, and direct overhead used to manufacture a product in order to calculate the manufacturing production cost.[c] Figure 5.6.1 shows the general breakdown of costs associated with manufacturing a product.

---

[c] When viewed from the companywide perspective, the sum of all material, labor, and overhead costs equals the company's sales cost, also referred to as the cost of goods sold.

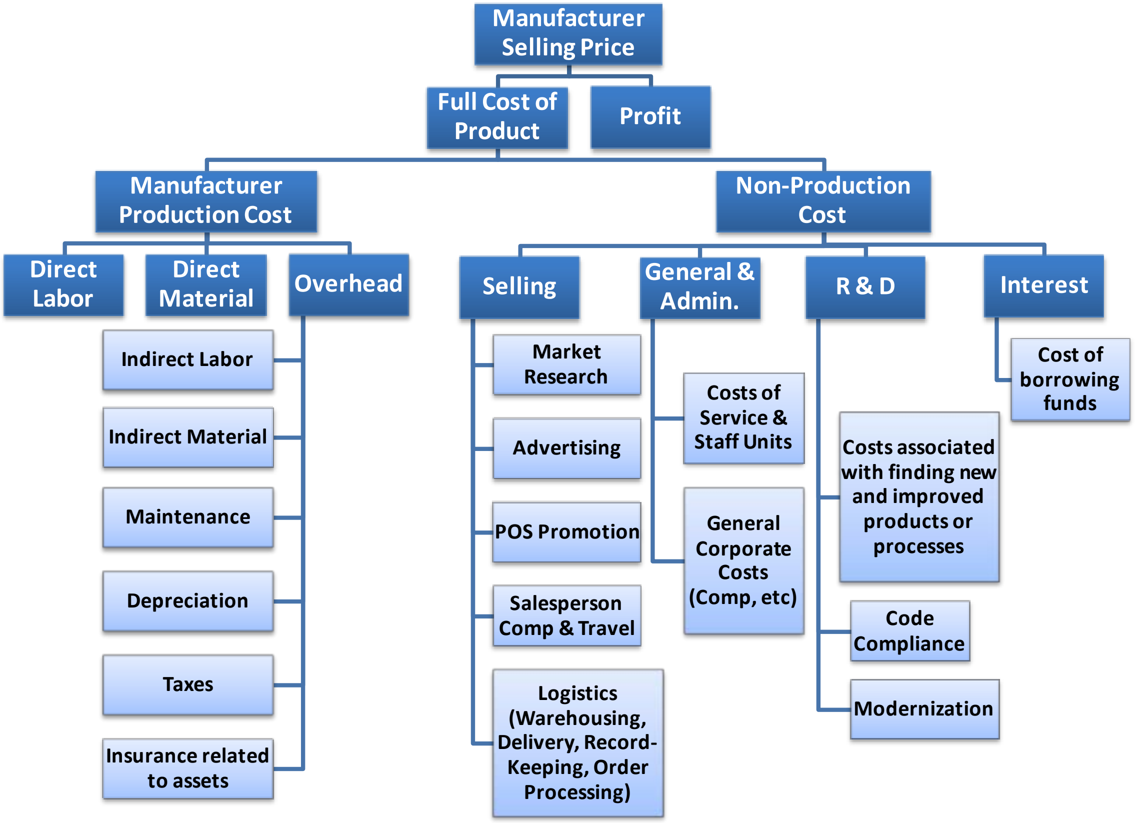

Figure 5.6.1 Full Production Costs

The full cost of the product is equal to the manufacturer selling price (MSP) minus profits. The full cost includes the MPC and the non-production cost.

5.6.6 Incremental Cost Estimates

Incremental costs were determined for design options and are applied to the estimated cost of the baseline-efficiency ice makers. The approach for estimating the incremental costs varied depending on the design option. Details in this calculation that are specific to individual design options are discussed in section 5.9. Aspects of the incremental cost calculation that were generally applied to multiple design options are discussed in this section.

Many of the design options involve replacement of a current component with a higher-efficiency component. For these design options, the increased price paid by the OEM for the new component represents the manufacturing cost increase—other elements of product cost such as overhead and capital expenditures would be insignificantly affected by these design changes. The appropriate price increases are discussed in section 5.9 by design option.

For some design changes, calculating the cost impact of the design change required direct use of the manufacturing cost model to determine changes to a number of parts. The baseline manufacturing cost was subtracted from the manufacturing cost of the modified design to determine the incremental cost of the design option. This approach was used in particular for condenser size increases.

5.6.6.1 G&A and Profit

DOE estimated the further addition to the MSP associated with general and administrative costs (G&A) and profit for the appliance industry as 25 percent of MPC. This adder was applied to all of the MPC estimates in order to determine MSP numbers. This markup is described in more detail in section 5.7.

5.7 MANUFACTURER MARKUP

Manufacturers and dealers apply a markup to cover their operating costs and profit margins in manufacturing and distribution. In the engineering analysis, DOE determined a manufacturer markup and applied it to the MPC to arrive at the MSP.

For the preliminary analysis, DOE usually develops this manufacturer markup multiplier by examining the annual reports and Securities and Exchange Commission (SEC) 10-K filings of several major manufacturers. Because the 10-K reports do not provide gross margin information at the subsidiary or business unit level, the gross margin as taken from the 10-K reports represents the average markups that parent companies apply over their entire range of product offerings. Each company considered may manufacture equipment other than commercial ice makers, and as such the parent company's gross margins could differ significantly from those of the subsidiary or business unit dedicated to the manufacturing of automatic commercial ice makers. Hence, DOE modified its usual approach for this rulemaking.

For this analysis, DOE used the gross margins of a single manufacturer whose total operations are most closely tied to the production of automatic commercial ice makers as the basis for its estimate of manufacturer markup because the other manufacturers examined derive most of their revenue from business units unrelated to ice maker manufacturing and/or have a very small market share. Considering this manufacturer's unique position of having an integrated dealer network, DOE corrected for their gross-margin-based markup by splitting it, assigning equal markup factors to the manufacturing and dealer units of the business, and arriving at an estimated 1.25 manufacturer markup factor. DOE intends to investigate this value during confidential interviews with manufacturers and will adjust its preliminary estimate accordingly.

5.8 ENERGY MODELING

DOE carried out detailed energy modeling of representative ice makers, and on design variations of these products that included one or more of the design options considered for the engineering analysis. This energy modeling work served as the basis for estimates of energy savings potential associated with the design options. The products selected for reverse engineering provided the basis for the energy modeling. Energy model input was determined for these products from the data collected during the reverse engineering work, described in section 5.5.2. Additional data, used both as input and for calibration of individual product energy models, was provided by energy testing as described in section 5.5.4. Using the energy modeling results and manufacturing cost modeling results for these designs allowed DOE to develop incremental cost estimates for multiple efficiency levels based on each of the baseline products analyzed.

DOE carried out energy modeling during this rulemaking using an improved version of the FREEZE simulation program. Section 5.8.1 describes this model briefly. A more detailed description of the program and its recent development is presented in appendix 5A.

5.8.1 FREEZE Model Overview

FREEZE is an energy model that simulates the performance of both batch and continuous ice makers. As applied to batch ice makers, FREEZE is a transient model that can calculate changes in operating conditions as a function of time. This feature is important for batch type machines for which refrigerant temperatures and pressures undergo large changes during the freeze cycle due to ice buildup on the evaporator.

The original version of FREEZE, developed by Anthony Varone in 1995 to operate in an MSDOS environment, has been upgraded to operate in a Windows environment. The model can simulate systems with a variety of configurations that include:

- batch or continuous ice making;
- air-cooled or water-cooled condensers, with a variety of air-cooled condenser configurations;
- water makeup for batch ice makers (a) entirely before the freeze cycle, (b) continuous fill as would be the case using a float valve, or (c) a hybrid combining these approaches;
- liquid-line/suction-line heat exchanger;
- choice of compressor; and
- choice of common refrigerants.

The FREEZE process is modeled using energy balances on the evaporator mass, ice mass, sump water, and water system. The evaporator plate, ice mass, sump water, and water system are each treated as lumped bodies, each at their own uniform temperature to calculate transient heat transfer between components. The energy balances account for heat transfer into and out of each component, energy storage, and enthalpy fluxes associated with refrigerant flow in and out, the freezing process, and makeup water. External heat transfer into the system includes ambient heat leak and the electrical energy associated with the water pump.

A major challenge to modeling batch type machines is calculating the overall evaporator thermal conductance, which varies throughout the cycle due to ice buildup on the evaporator. This is accomplished using user-defined curves for heat transfer versus ice mass on the evaporator that account for conduction heat transfer from the water, through the ice, and through the evaporator. The evaporator thermal conductance (evaporator UA) curves are generated by a separate spreadsheet-based conduction heat transfer analysis and depend on the specific evaporator design. Sixth-order best-fit polynomial curve fits for evaporator thermal conductance as a function of ice mass on the evaporator are determined based on this separate analysis—these curve fits are used in the FREEZE model to represent the evaporator thermal conductance. The evaporator UA (the product of the overall heat transfer coefficient and the heat transfer surface area) curves were developed for the two most common evaporator types. Refrigerant heat transfer coefficients are calculated within the program and are used along with the evaporator thermal conductance to calculate the overall thermal conductance from the water to the refrigerant.

The refrigerant cycle model is a descendant of the National Institute of Science and Technology (NIST) CYCLE7 model that has been modified to incorporate the transient effects associated with ice buildup on the evaporator plate. There is a choice of six refrigerants, including R-404A, the most common refrigerant used in ice-making applications. Refrigerant thermodynamic and thermophysical properties are calculated using REFPROP 8.0.

Continuous ice makers operate at steady-state. Thus, conditions do not change with time. Program output includes ice production rate, energy consumption, and refrigerant cycle conditions. As with the modeling of batch type machines, evaporator thermal performance is a user-defined parameter and is not calculated within the program. Additional inputs include ice hardness of the output ice, auger motor power and efficiency, and heat leak from the ambient into the evaporator.

Compressor performance is determined from user-created data files based on compressor maps provided by compressor manufacturers. Compressor capacity and power are adjusted at each point in the calculation to reflect suction, discharge, and liquid conditions different from rating conditions.

Machines with either air-cooled or water-cooled condensers can be modeled. For air-cooled condensers, refrigerant and air side heat transfer coefficients and pressure drop are calculated within the program using models developed recently for the Efficient Refrigerator Analysis (ERA) program as part of the residential refrigeration product rulemaking. 76 FR 57516, 57531 (Sept. 15, 2011). Required heat exchanger input data include tube diameter and wall thickness, number of tubes, tube spacing, fin type, fin spacing, fin material and thickness, air flow rate and inlet temperature, fan power, and refrigerant outlet subcooling.

Water-cooled condenser operation is based on maintaining a constant condensing pressure and therefore temperature, and is thus modeled based on maintaining a constant condensing bubble-point temperature as defined by the user. User inputs include condensing temperature, refrigerant subcooling, and pressure drop.

The expansion device (*e.g.*, thermostatic expansion valve) is not modeled explicitly. Instead, it is simulated in the model as maintaining a constant evaporator superheat throughout the freeze cycle as specified by the user.

The FREEZE program can model systems with a liquid-line/suction-line heat exchanger and accounts for suction line heat gain from the ambient and refrigerant pressure drop in the suction line. User inputs include heat exchanger effectiveness, suction line heat transfer, and pressure drop.

Each freeze cycle requires a flow of water necessary to flush out impurities from the system and to provide water to make up for the water harvested as ice. Generally, there are two strategies for providing makeup water. The first, referred to as a batch fill strategy, involves filling the sump with the water needed to dilute impurities and to produce a batch of ice. The second strategy, referred to as a continuous fill strategy, involves supplying a flow of makeup water corresponding to the rate at which ice is frozen on the evaporator plate. Both strategies can be modeled. The continuous fill approach allows initiation of filling at sump levels other than

100 percent—this is a hybrid batch/continuous fill approach in which the water level drops as ice freezes until the water level reaches the predetermined level.

Evaporator cold compartment configurations vary widely and thus are not amenable to general analytical treatment. Some designs enclose the evaporator in a fully insulated cabinet with a plastic liner, while for others the evaporator cold compartment is formed by cabinet sheet metal with Styrofoam or batt insulation attached. Some designs may have parts of walls or entire walls that are uninsulated. Some place the sump entirely inside the cold compartment while others have the sump straddling the cold compartment and the compressor compartment. Because of the wide variety of designs, the model does not calculate the heat leak into the cold compartment from basic cabinet design parameters. Instead, it is modeled using a user-defined evaporator cold compartment thermal conductance parameter.

The harvest process involves bypassing the condenser to allow hot refrigerant to flow directly from the compressor to the evaporator to provide the heat input to free the ice from the plate. A number of manufacturers also assist the harvest process either by mechanical means or by using the heat contained in the makeup water. In FREEZE, the effects of harvest on performance are determined based on input data for the harvest time, ice meltage, and harvest energy consumption.

Parasitic power consumption of components such as control circuit boards, solenoid valves, and harvest assist devices are modeled by entering the power consumption of each component.

5.9 DESIGN OPTIONS

After conducting the screening analysis described in chapter 4, DOE considered the remaining technologies in the design option analysis. Table 5.9.1 lists the design options DOE considered for each equipment class. Some design options are applicable only to certain types of equipment. Following the table is a description of how DOE applied each of the design options during the engineering analysis. See chapter 3 of the preliminary TSD for background descriptions of the technologies.

Table 5.9.1 Design Options by Equipment Class

Ice Maker Type	Equipment Class	Compressor Upgrade	Condenser Fan Motors	Pump Motors	Auger Motors	Air-Cooled Condensers	Harvest Assist	Batch Fill
Batch	IMH-W-B	✓		✓			*	*
	IMH-A-B	✓	✓	✓		✓		
	RCU-B	✓	✓	✓		✓		
	SCU-W-B	✓		✓				
	SCU-A-B	✓	✓	✓		✓		
Continuous	IMH-W-C	✓			✓			
	IMH-A-C	✓	✓		✓	✓		
	RCU-C	✓	✓		✓	✓		
	SCU-W-C	✓			✓			
	SCU-A-C	✓	✓		✓	✓		

* Used in a few limited cases where this design option was applicable.

5.9.1 Improved Compressor Efficiency

DOE considered the substitution of higher-efficiency compressors for all equipment classes. DOE acquired compressor performance data from compressor manufacturers for use in the energy analysis, including capacity and power input for scroll and reciprocating compressors with capacities of 1,000 to 36,000 British thermal units per hour (Btu/h) rated at AHRI 540 Medium Temperature testing conditions. Table 5.9.2 lists the AHRI 540 Medium Temperature operating test conditions. Not all compressor vendors provided compressor performance data at these operating conditions. DOE adjusted the obtained data if necessary to represent performance at these standard conditions. The nominal energy efficiency ratio (EER)[d] for the available compressors is summarized as a function of compressor capacity in Figure 5.9.1 .

Table 5.9.2 AHRI 540 Medium Temperature Operating Test Conditions

Condensing Temperature	120 ^{o}F
Evaporating Temperature	20 ^{o}F
Suction Temperature	40 ^{o}F
Subcooling	0 ^{o}F

---

[d] EER is equal to compressor capacity in British thermal units per hour divided by compressor input power in watts.

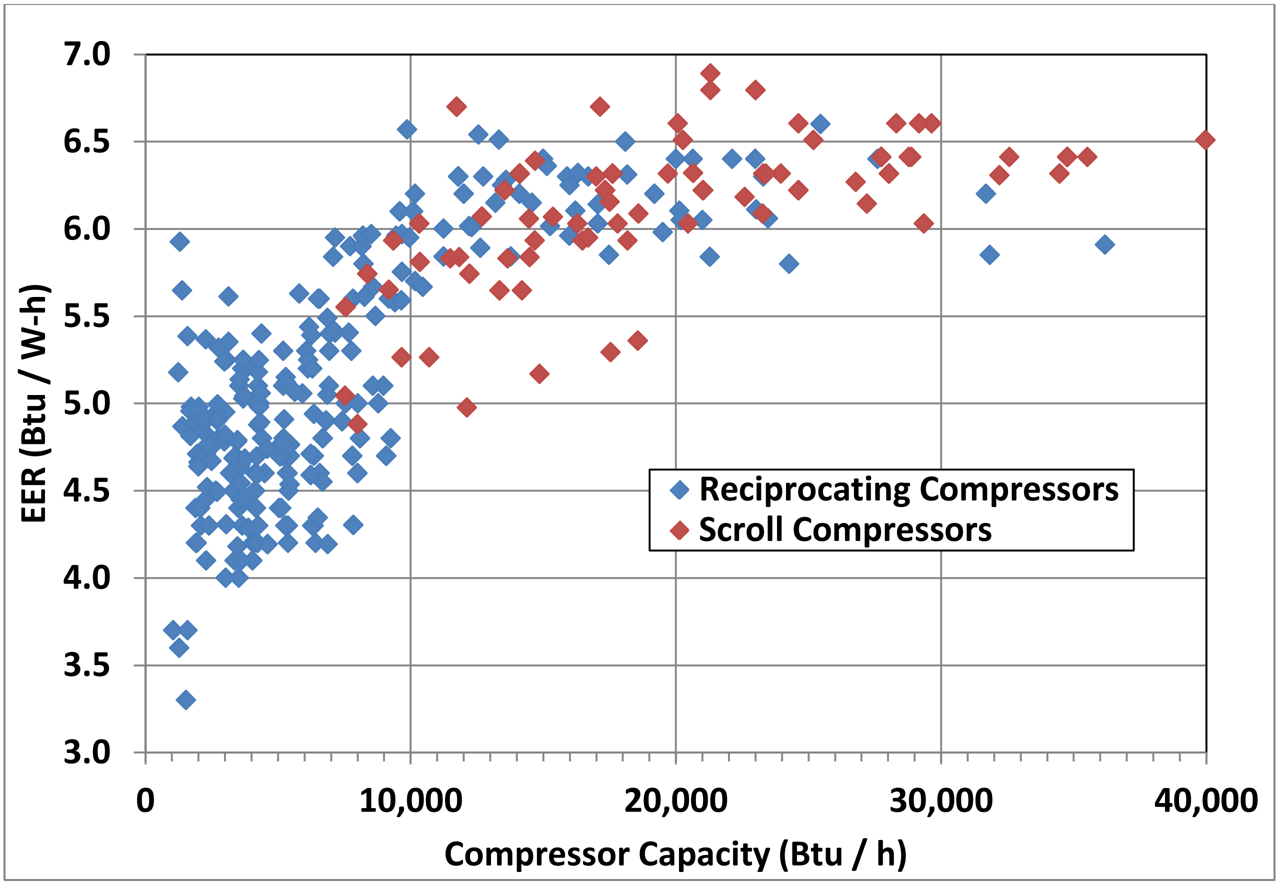

Figure 5.9.1 Efficiency Curve for Typical Compressor Capacities Used in Commercial Ice Makers

DOE considered higher-efficiency replacement compressors, identified through discussions with compressor suppliers or review of compressor supplier websites, with a capacity within 10 percent of the replaced compressor. The energy model accounted for the impact on ice maker energy use of both the EER improvement and the capacity change in the analysis.

5.9.1.1 Compressor Cost Data

DOE developed a cost correlation for medium temperature compressors as part of the commercial refrigeration equipment (CRE) rulemaking, relating the compressor cost to its capacity. DOE also adopted an approach for evaluating the potential for efficiency improvement and the cost associated with higher efficiency as part of the CRE rulemaking, in which DOE assumed that a 10 percent compressor EER improvement was possible for all equipment, and that this would increase compressor cost by 5 percent.[6] DOE adopted a slightly modified approach for the current rulemaking. DOE assigned the cost derived using the cost correlation to median-EER compressors of a given capacity. Further, DOE applied an exponential cost relationship for higher-EER compressors that is consistent with a 5 percent cost increase for 10 percent EER improvement. However, DOE based the potential for compressor efficiency improvement on the available compressor data, rather than assuming a fixed 10 percent EER improvement. The cost curve applicable for median-EER compressors is shown in Figure 5.9.2.

The cost curve is based on capacity at modified operating conditions, at 15 °F evaporating temperature and 95 °F condensing temperature. On average, the capacity for these conditions is 1.29 times the capacity at the AHRI 540 rating conditions.

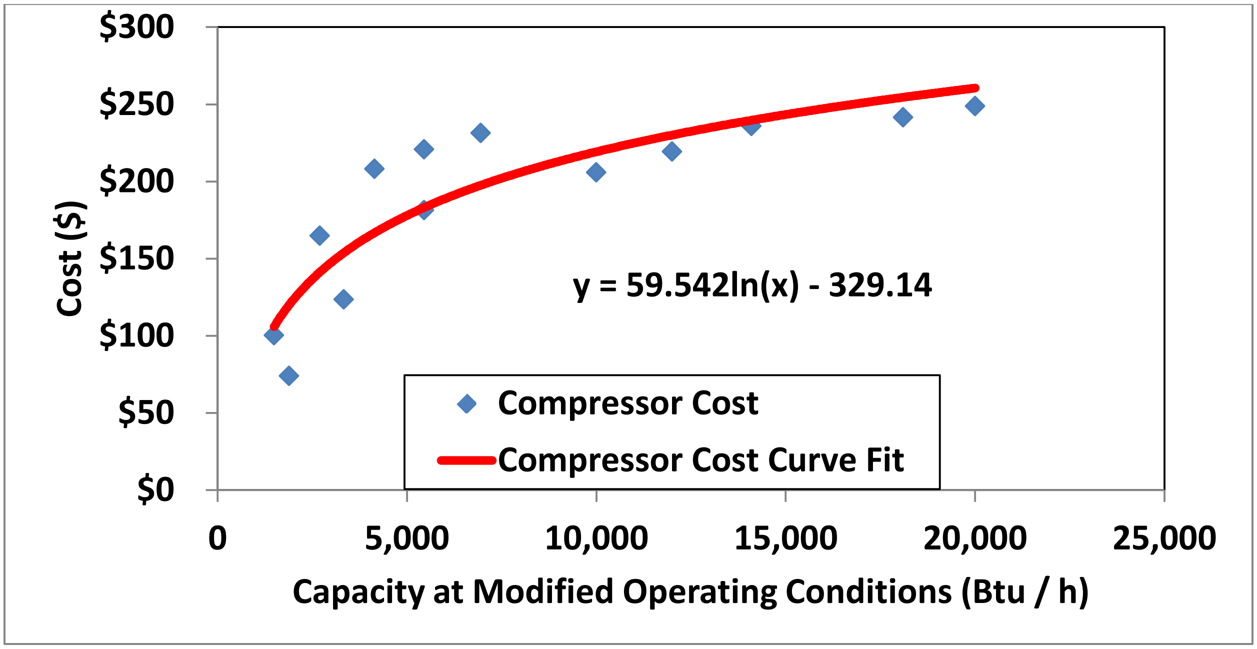

Figure 5.9.2 Cost Curves for Medium Temperature Compressors Used in Commercial Ice Makers

When considering compressor efficiency improvement for standard-size products, DOE used the performance data of specific higher-efficiency compressors in the energy analysis. DOE selected the alternative compressors to have nearly the same capacity as the baseline compressors to ensure nearly identical performance except for compressor power input.

DOE used the following exponential relationship to determine the cost increase associated with higher-EER compressors:

$$New\ Cost\ =\ Baseline\ Cost\ \times\ 1.05^{\left[\frac{log(New\ EER\ \div Old\ EER)}{log(1.1)}\right]}$$

For a 10 percent increase in EER, this relationship yields a 5 percent increase in cost, consistent with the approach used for the CRE rulemaking.

5.9.2 Increased Air-Cooled Condenser Surface Area

The condenser transfers heat from the refrigerant to the ambient air. A larger surface area allows the heat transfer to occur more efficiently, allowing the refrigerant circuit to operate with a lower condensing temperature. DOE considered an increase in condenser surface area for all air-cooled products analyzed. For IMH and SCU ice makers, the size increase was limited by available space. DOE reviewed the space available in the teardown products that served as the basis for the energy modeling to determine how much size increase would be possible without requiring an increase in the overall equipment size. In some cases, DOE determined that no size increase was possible. For RCU ice makers, DOE considered condenser size increases that required an increase in remote condenser size.

Condenser size increases were implemented in the energy analysis through direct adjustment of the input parameters describing the condenser geometry. DOE increased either the number or length of tube rows as appropriate for the space available for size increase, increasing air flow to maintain a constant face velocity, or maintaining constant air flow, depending on which approach was most effective in reducing overall energy use. DOE accounted for the impact of condenser size increase and air flow changes on condenser fan power input, assuming that for the initial design (1) three-quarters of the total condenser air flow system pressure drop is associated with pressure drop through the condenser itself; (2) pressure drop is proportional to condenser face velocity; and (3) fan power input is proportional to air flow times pressure drop.

The cost associated with the condenser size increase was calculated using the manufacturing cost model with model inputs adjusted for condenser geometric details. During the NOPR phase, DOE expects to evaluate the need to also consider when an increase in condenser size necessitates addition of a receiver, or an increase in size of an existing receiver, in order to ensure that the increased refrigerant charge will be properly managed for all ice maker operating modes.

5.9.3 Evaporator Size Increase for Continuous Ice Makers

The evaporator transfers heat from the freezing liquid water to the refrigerant. Larger surface area allows the heat transfer to occur more efficiently, allowing the refrigeration system to transfer the same amount of heat with a higher evaporating temperature. DOE considered an increase in evaporator surface area for some continuous ice makers analyzed. In these cases, DOE assumed that the cost for the evaporator assembly would be 10 percent higher for a 50 percent increase in surface area. DOE implemented these changes in the energy model by increasing the model input UA value (heat transfer coefficient times effective evaporator surface area, with overall units of Btu/h-°F) consistent with the surface area increase.

5.9.4 Condenser Fan Motors

A condenser fan in a commercial ice maker draws in ambient air and circulates it through the condenser coils and over the compressor shell, thereby cooling the condensing refrigerant and the compressor. The motors used to run these fans are typically shaded pole (SP) or permanent split capacitor (PSC) motors with shaft power outputs ranging from 3 to 750 W, depending on the ice maker's harvest capacity. DOE analyzed the efficiencies of these motors through and found that permanent magnet DC (PMDC) fan motors are more efficient than SP or PSC motors currently used in baseline commercial ice makers.

Table 5.9.3 lists the shaft output power range and efficiency ranges of different types of motors suitable for use in condenser fans. This information was obtained through supplier interviews, motor literature, and examination of the motors used in the reverse engineering ice makers. In the preliminary engineering analysis, DOE assumed that the efficiencies of the three motor types are 25 percent for SP, 45 percent for standard-efficiency PSC, 65 percent for highest-efficiency PSC, and 75 percent for PMDC. While these efficiencies may apply only for a specific shaft power level, DOE assumed that the efficiencies at different shaft power output levels scale similarly. For example, at a lower shaft power level a shaded power motor may have an efficiency of 15 percent. DOE then calculated the efficiency of a replacement standard-efficiency PSC motor as 15% × 45 ÷ 25 = 27%.

Table 5.9.3 Expected Shaft Power Output Range and Efficiencies for Different Types of Motors

Motor Type	Output Power Range	Efficiency Range
Shaded Pole (SP)	3 to 60 W	14 to 25%
Permanent Split Capacitor (PSC)	9 to 750 W	50 to 70%
Permanent Magnet Direct Current (PMDC)	3 to 750 W	75 to 83%

Based on the information obtained from the sources mentioned above, DOE developed a matrix of costs of different motor types as a function of shaft output power. This information, which was used for the preliminary engineering analysis, is summarized in Table 5.9.4.

Table 5.9.4 Motor Cost Information Use for Preliminary Engineering Analysis

Shaft Power *W*	Horsepower	Shaded Pole	Standard-Efficiency PSC	Highest-Efficiency PSC	Permanent Magnet DC
6	0.008	$10	$14		$16
9	0.012	$12	$18		$22
12	0.016	$14	$20		$24
25	0.034	$26	$32	$41	$36
37	0.050	$28	$53	$66	$93
60	0.080	$30	$70	$89	$110
100	0.134		$90	$115	$132
200	0.268		$108	$141	$155
373	0.500		$128	$166	$173
560	0.750		$143	$184	$190
746	1.000		$155	$200	$205

5.9.5 Auger Motors

Augers are integrated into the evaporators of continuous commercial ice makers, as discussed in chapter 3 of the preliminary TSD. Auger assemblies incorporate a motor and a gear drive to reduce the motor speed to that of the auger. The motors typically used for augers in ice makers using single-phase power are PSC or capacitor start induction run (CSIR) motors with shaft power output between 200 and 400 W.

For the preliminary engineering analysis, DOE used the performance and cost information obtained for condenser fan motors to estimate both the efficiency improvement and the cost impact of switching to other motor types. DOE assumed for this analysis that CSIR motor performance and cost are equivalent to the performance and cost of standard-efficiency PSC motors. DOE will collect additional information to allow adjustment of this approach in the NOPR phase as appropriate.

5.9.6 Pump Motors

Water pumps are used in batch commercial ice makers to transport water from the water sump to the ice tray where water is frozen. The motors used for these pumps are exclusively SP motors with shaft power outputs between 6 and 15 W. As with auger motors, DOE used the information collected for condenser fan motors to evaluate pump motor design options in the preliminary engineering analysis, assuming that this information is also representative of the potential for performance improvement and cost increase for pump motors.

5.10 ENGINEERING ANALYSIS RESULTS

This section presents the engineering analysis results, including the incremental cost curves. DOE generated cost-efficiency curves for ice maker equipment classes, based on combinations of individual design options. DOE normalized the curves by converting to costs at specific efficiency levels, as previously defined for each equipment class (see section 5.4) for simplified downstream analysis.

Table 5.10.1 presents MPC, MSP, and water use characteristics for baseline batch ice makers. The table also indicates which equipment classes were used for extrapolation of results for equipment classes that were not directly analyzed.

Table 5.10.2 presents incremental MSP for the evaluated efficiency levels for batch ice makers. The representative harvest capacities indicated in the tables are those of the products analyzed—they indicate the variation of baseline equipment characteristics and incremental MSP as a function of harvest capacity within given equipment classes.

Table 5.10.1 Batch Ice Maker Baseline Characteristics and Extrapolation Approach

Equipment Class	**Representative Harvest Capacity** ***lb/24 hours***	**MPC**	**MSP**	**Potable Water Use** ***gal/ 100 lb***	**Condenser Water Use** ***gal/ 100 lb***	**Extrapolation: Results for this equipment class based on extrapolation from the following equipment class**
IMH-W						
Small	300	$1,668	$2,085	22	156	IMH-A-Small-B
Medium	850	$2,762	$3,453	21	148	Direct Analysis
Large	1,500	$4,055	$5,069	20	137	IMH-A-Large-B
	2,600	$6,571	$8,214			Direct Analysis
IMH-A						
Small	300	$1,671	$2,089	22	NA	Direct Analysis
Large	800	$2,447	$3,059	20		Direct Analysis
	1,500	$4,035	$5,044			Direct Analysis
RCU						
Small	700	$2,882	$3,602	21	NA	RCU-Large-B
Large	1,500	$5,097	$6,371	20		Direct Analysis
	2,400	$6,205	$7,756			Direct Analysis
SCU-W						
Small	110	$1,806	$2,258	29	165	SCU-A-Small-B
Large	300	$1,815	$2,269	28	165	Direct Analysis
SCU-A						
Small	110	$1,806	$2,258	30	NA	Direct Analysis
Large	200	$1,810	$2,263	26		SCU-A-Small-B

Table 5.10.2 Incremental Manufacturer Selling Price Results for Batch Ice makers

Equipment Class	Max Available	Representative Harvest Capacity *lb/24 hours*	EL2*	EL3	EL4	EL5	EL6	Max Tech	
								Level	Cost
IMH-W			10%	15%	20%				
Small	25%	300	$32					14%	$38
Medium	22%	850	$25					10%	$25
Large	23%	1,500	$12					11%	$18
	8%	2,600						3%	$12
IMH-A			10%	15%	20%				
Small	24%	300	$10	$24	$55			20%	$55
Large	21%	800	$10	$29	$126			20%	$126
		1,500	$12	$90				15%	$90
RCU			9%	15%	20%	25%			
Small	20%	700	$12	$50				16.5%	$68
Large	40%	1,500	$16	$81				16.5%	$103
	27%	2,400	$147					14%	$204
SCU-W			7%	15%	20%	25%	30%		
Small	25%	110	$10	$27	$41			24%	$55
Large	28%	300	$10	$20	$27	$34	$43	39%	$67
SCU-A			7%	15%	20%	25%	30%		
Small	32%	110	$10	$31	$45	$56		28%	$62
Large	31%	200	$17	$35	$46	$60		25%	$60

* EL = efficiency level; EL1 is the base line efficiency level while EL2 through EL6 represent increased efficiency levels.

Table 5.10.3 and Table 5.10.4 present the engineering analysis results for continuous ice makers. Table 5.10.3 does not present potable water use, since this is assumed to be 12 gal/100 lb for all continuous ice makers. The table presents baseline ice maker condenser water use with adjustment for ice hardness as established in the test procedure final rule. 77 FR at 1597 (Jan. 11, 2012). The efficiency levels for RCU and SCU-W continuous ice makers in Table 5.10.4 are represented both in comparison with the batch ice maker efficiency levels and how these levels would compare with the continuous ice maker equipment class trial baseline.

Table 5.10.3 Continuous Ice Maker Baseline Characteristics and Extrapolation Approach

Equipment Class	**Representative Harvest Capacity** ***lb/24 hours***	**MPC**	**MSP**	**Condenser Water Use** ***gal/ 100 lb***	**Extrapolation: Results for this equipment class based on extrapolation from the following equipment class**
IMH-W					
Small	800	$2,748	$3,435	110	IMH-A-Small-C
Large	1,000	$3,125	$3,906	110	IMH-A-Small-C
	1,800	$4,633	$5,791		IMH-A-Small-C
IMH-A					
Small	310	$1,825	$2,281	NA	Direct Analysis
	820	$2,786	$3,483		Direct Analysis
Large	1,000	$3,125	$3,906		IMH-A-Small-C
	1,800	$4,633	$5,791		IMH-A-Small-C
RCU					
Small	700	$3,055	$3,819	NA	RCU-Large-B
Large	1,500	$4,563	$5,704		Direct Analysis
SCU-W					
Small				110	No Analysis*
Large	300	$1,778	$2,223	110	SCU-W-Large-B
SCU-A					
Small	110	$1,769	$2,211	NA	SCU-W-Small-B
Large	300	$1,778	$2,223		IMH-A-Small-C
	670	$2,503	$3,129		IMH-A-Small-C

* No products of this equipment class were identified in product databases.

Table 5.10.4 Incremental Manufacturer Selling Price Results for Continuous Ice Makers

Equipment Class	Max Available	Representative Harvest Capacity *lb/24 hours*	EL2*	EL3	EL4	EL5	EL6	Max Tech	
								Level	**Cost**
IMH-W			10%	15%	20%	25%	30%		
Small	35%	800	$5	$12	$20	$27	$78	33%	$78
Large	20%	1,000	$16	$24	$38			24%	$75
		1,800	$18	$28	$50			24%	$125
IMH-A			10%	15%	20%	25%	30%		
Small	37%	310	$21	$35	$49	$63	$162	30%	$162
		820	$10	$20	$28	$36	$44	42%	$138
Medium	32%	1,000	$18	$25	$33	$41	$94	35%	$136
		1,800	$25	$34	$43	$52	$126	35%	$216
RCU			Batch Std. (7%)	EL1 -10% (17%)	EL1 -15% (22%)	EL1 -20% (26%)	EL1 -25% (30%)		
Small	26%	700	$9	$68				16.5%	$68
Large	42%	1,500	$10	$103				16.5%	$103
SCU-W			Batch Std. -20% (3%)	Batch Std. -25% (10%)	Batch Std. -30% (16%)				
Small	NA**								
Large	15%	300	$4	$12	$20			18%	$22
SCU-A			7%	15%	20%	25%	30%		
Small	11%	110	$24	$46				18%	$51
Large	39%	300	$-	$17	$30	$46	$62	36%	$162
		670	$-	$37	$65	$98	$135	36%	$335

* EL = efficiency level; EL1 is the base line efficiency level while EL2 through EL6 represent increased efficiency levels.

** No products of this equipment class were identified in product databases.

REFERENCES

1. Consortium for Energy Efficiency. *High Efficiency Specifications for Commercial Ice Makers*. July 2011. Boston, MA. <www.cee1.org/com/com-kit/files/IceSpecification01Jul2011.pdf>

2. American Metals Market. (Last accessed in 2011.) <www.amm.com>

3. U.S. Department of Labor, Bureau of Labor Statistics. *Producer Price Indices*. (Last accessed in 2011.) <www.bls.gov/ppi>

4. U.S. Department of Commerce, Bureau Economic Analysis. *Gross Domestic Product Implicit Price Deflator*. (Last accessed in 2011.) <https://bea.gov/bea/dn/nipaweb/TableView.asp#Mid>

5. *Plastic News*. Resin Pricing. (Last accessed in 2011.) <www.plasticsnews.com/subscriber/headlines.phtml>

6. U.S. Department of Energy–Office of Energy Efficiency and Renewable Energy. Preliminary Technical Support Document (TSD): Energy Conservation Program for Certain Commercial and Industrial Equipment: Commercial Refrigeration Equipment. March 2011. Chapter 5, Table 5.6.18, pp. 5–26. Washington, D.C. <www1.eere.energy.gov/buildings/appliance_standards/commercial/pdfs/cre_pa_tsd_ch5_engineering.pdf.>