Designation: E 869 – 93 (Reapproved 1998)

Standard Test Method for Performance Evaluation of Fuel Ethanol Manufacturing Facilities[1]

This standard is issued under the fixed designation E 869; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reapproval. A superscript epsilon (ε) indicates an editorial change since the last revision or reapproval.

1. Scope

1.1 This test method covers the determination of performance characteristics of fuel ethanol manufacturing facilities.

1.2 This test method is applicable for all starch, sugar, and combination starch/sugar based fermentable feedstocks.

1.3 This test method is applicable to both batch and continuous fuel ethanol manufacturing processes.

1.4 *This standard does not purport to address all of the safety problems, if any, associated with its use. It is the responsibility of the user of this standard to establish appropriate safety and health practices and determine the applicability of regulatory limitations prior to use.*

2. Referenced Documents

2.1 *ASTM Standards:*

D 1826 Test Method for Calorific Values of Gases in Natural Gas Range by Continuous Recording Calorimeter[2]

D 2382 Test Method for Heat of Combustion of Hydrocarbon Fuels by Bomb Calorimeter (High-Precision Method)[3]

D 2458 Flow Measurement of Water[4]

D 3286 Test Method for Gross Calorific Value of Coal and Coke by the Isothermal Bomb Calorimeter[2]

D 3590 Test Method for Total Kjeldahl Nitrogen in Water[5]

E 100 Specification for ASTM Hydrometers[6]

E 711 Test Method for Gross Calorific Value of Refuse-Derived Fuel by the Bomb Calorimeter[6]

E 870 Test Methods for Analysis of Particulate Wood Fuels[7]

2.2 *Association of Official Analytical Chemists (AOAC) Standards:*[8]

10.231 Test for Moisture in Brewers Grains

14.062 Test for Moisture in Wheat, Rye, Oats, Corn, Buckwheat, Rice, Barley, and Soybeans and their Products Except Cereal Adjuncts

14.073–14.074 Test for Starch in Cereals

31.005–31.008 Test for Moisture in Sugars

31.051 Test for Glucose in Sugars and Syrups

31.056 Test for Fructose in Sugars and Syrups

31.060 Test for Maltose in Sugars and Syrups

31.062 Test for Lactose in Sugars and Syrups

2.3 *Standard Methods (SM) for Analysis of Water and Wastewater:*[9]

206 B Test for Fats, Oils, and Grease

209 C Test for Total Suspended Solids

507 Test for Biochemical Oxygen Demand, Five Day (BOD_5)

3. Terminology

3.1 *Definitions:*

3.1.1 *cycle time*—the time required by an alcohol plant to complete one cycle. The determination of the cycle time for a batch process is illustrated in Fig. 1 and for a continuous process in Fig. 2.

3.1.2 *normal operating conditions*—the usual range of physical conditions for which a facility was designed to operate.

3.1.3 *production cycle*—the series of operations required to process through the facility a quantity of feedstock mixed with water having a volume equal to the typical volume of the fermentation system and return the facility to the configuration at the start of the cycle. The quantity of water mixed with the feedstock shall be as per specification for normal operation. This volume is equal to the sum of the working volumes of all fermenters in a batch fermentation process. This volume is equal to the sum of the working volumes of each stage of fermentation in a continuous fermentation process. The determination of the production cycle for a batch process is illustrated in Fig. 1 and for a continuous cycle in Fig. 2. Any differences in the configuration between the start and end of the test shall be noted in Table 1.

[1] This test method is under the jurisdiction of ASTM Committee E-48 on Biotechnology and is the direct responsibility of Subcommittee E48.05 on Biomass Conversion Systems.

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[2] *Annual Book of ASTM Standards*, Vol 05.05.

[3] *Annual Book of ASTM Standards*, Vol 05.02.

[4] Discontinued—See 1981 *Annual Book of ASTM Standards*, Part 31.

[5] *Annual Book of ASTM Standards*, Vol 11.01.

[6] *Annual Book of ASTM Standards*, Vols 05.03 and 14.03.

[7] *Annual Book of ASTM Standards*, Vol 11.05.

[8] Available from Association of Official Analytical Chemists, 1111 N. 19th St., Arlington, VA 22209.

[9] Available from American Public Health Association, 1015 15th St. N.W., Washington, DC 20005.

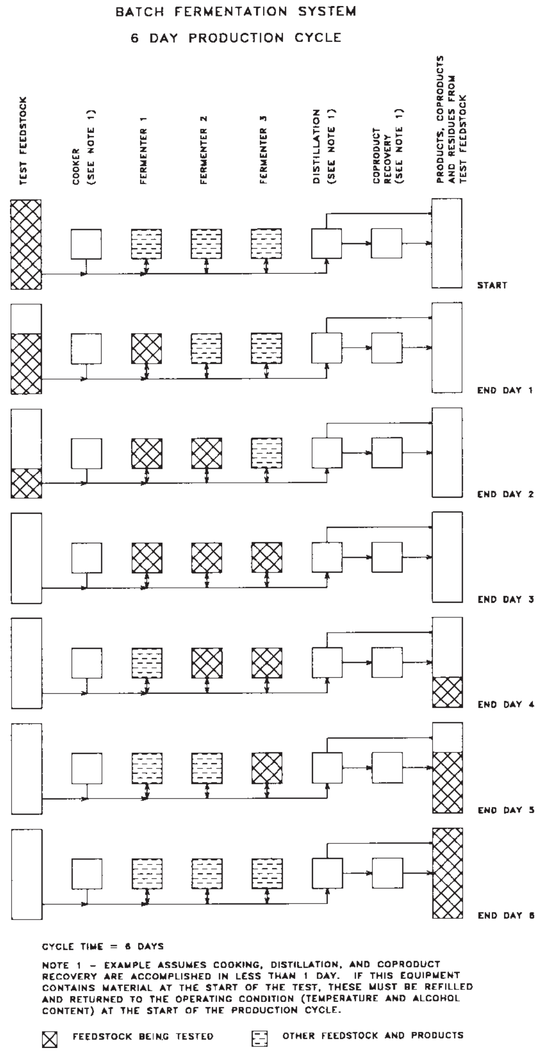

FIG. 1 Production Cycle and Cycle Time for Batch Process 6 Day Production Cycle

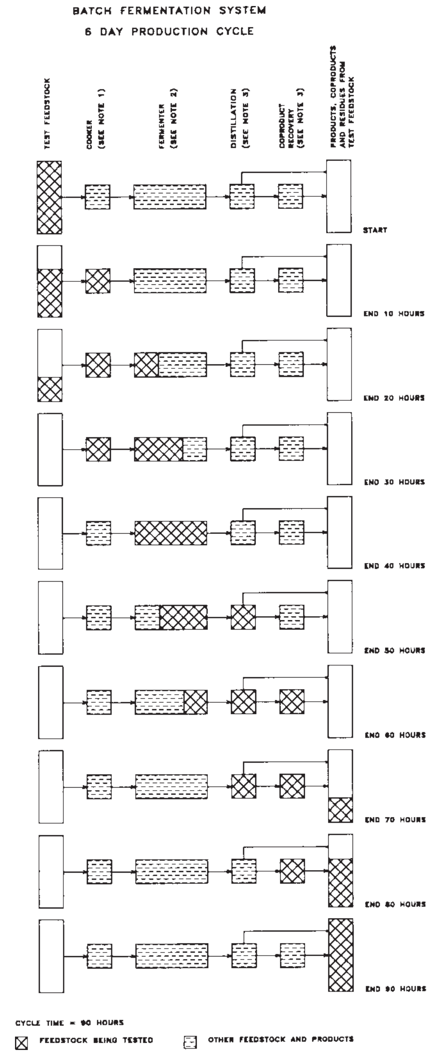

FIG. 2 Production Cycle and Cycle Time for Continuous Process 90 h Production Cycle

4. Summary of Test Method

4.1 A fuel ethanol manufacturing facility's performance shall be characterized by four main parameters. These are (*1*) conversion efficiency, (*2*) energy for conversion, (*3*) production rate, and (*4*) mass balance. This test method shall establish the procedures required to measure, interpret, and assign values for these parameters. This test method shall consider each facility as a single "black box" and, for the purpose of these procedures, a description of the black box shall be established and recorded prior to testing. This black box may include systems for feedstock preparation, conversion of carbohydrates to alcohol, and separation of alcohol and co-products.

4.2 *Conversion Efficiency*—This parameter represents the facility's capability to convert a feedstock into fuel ethanol. This shall be expressed as the ratio of the actual fuel ethanol yield per unit mass of dry feedstock to theoretical fuel ethanol yield per unit mass of dry feedstock.

4.3 *Energy for Conversion*—These parameters (electrical, thermal, and total energy) reflect the energy required to run the facility. These shall be expressed as a ratio of the electrical, thermal, and total energy required for production of a given volume of fuel ethanol to the volume of fuel ethanol produced (in moisture-free fuel ethanol).

4.4 *Production Rate*—This parameter of performance expressed the facility's ability to convert a feedstock to fuel ethanol during a specified unit of time. Since this test method shall apply to a large variety of facility sizes and configurations, this parameter can be expressed as the total volume of fuel ethanol produced (on a moisture-free basis) divided by the cycle time as defined in 3.1.1.

4.5 *Mass Balance*—This performance parameter measures the facility's production of fuel ethanol and other co-products. This shall be represented as a mass ratio of these products to the feedstock all on a moisture-free basis.

5. Significance and Use

5.1 This test method shall yield data that will form a "performance profile" for a fuel ethanol manufacturing facility. The significance of this profile is that it can be compared directly to another facility's performance profile and yield a relative measurement and shall provide a measure of expected facility performance under field conditions. Based on the four

TABLE 1 Data Collection Form for Fuel Ethanol Plant Performance Evaluation

(*1*) Plant cycle date and time	
(Record for each cookbatch)	
Start:	______
Finish:	______
(*2*) Plant conditions at test start	
Cooker:	
Volume	______
Temperature	______
Alcohol proof of contents	______
Fermenters (repeat for each unit):	
Volume	______
Temperature	______
Alcohol proof of contents	______
Distillation:	
Volume	______
Temperature	______
Alcohol proof of contents	______
Co-product recovery:	
Volume	______
Temperature	______
Alcohol proof of contents	______
(*3*) Feed stock	
Type:	
Analysis:	
Moisture, wt %	______
Starch, wt %	______
Glucose, wt%	______
Fructose, wt %	______
Maltose, wt %	______
Lactose, wt%	______
Density, lb/unit volume	______
Quantity used during cycle, units	______
(*4*) Water added to process	
Fresh water, gal/°F	______
Setback (recycle) water, gal/°F	______
Alcohol content, proof	______
Biochemical oxygen demand (BOD), mg/L	______
Total suspended solids (TSS), mg/L	______
Fats, oils, and grease (FOG), mg/L	______
Alcohol proof	
(*5*) Enzymes yeast, process chemicals used—list separately	
Type, quantity	______
	______
	______
	______
(*6*) Alcohol produced	
Product recovered, gal	______
Proof (adjusted to 60°F)	______
Temperature, °F	______
Losses:	______
Thin stillage, flow/proof	______
Spent solids, flow	______
Wt % alcohol	______
(*7*) Distillers grains recovered	
Quantity, lb	______
Analysis:	______
Moisture, wt %	______
Protein, wt%	______
Starch test, Positive/Negative	______
(*8*) Energy consumed	
Electrical meter reading (kWh)	______
Start	______
Stop	______
Fuel (Type:) Units	______
Start	______
Stop	______
(*9*) Process wastewater	
Discharge temperature, °F	______
Quantity, gal	______
BOD, mg/L	______
TSS, mg/L	______
FOG, mg/L	______
(*10*) Plant conditions at test finish	
Cooker:	
Volume	______

TABLE 1 *Continued*

Temperature	______________________________
Alcohol proof of contents	______________________________
Fermenters (repeat for each unit):	
Volume	______________________________
Temperature	______________________________
Alcohol proof of contents	______________________________
Distillation:	
Volume	______________________________
Temperature	______________________________
Alcohol proof of contents	______________________________
Co-product recovery:	
Volume	______________________________
Temperature	______________________________
Alcohol proof of contents	______________________________
Brief description of facilities included in test program	
Data recorded by: ______________________	

main parameters highlighted above, facilities of significantly different designs can be compared relatively.

5.2 The single black box technique applied to performance evaluation examines only the overall input/output relationship. This implies that the operation of the facility during the tests shall be conducted to achieve design conditions in accordance with established procedures.

6. Procedure

6.1 This test method calls for measurement of the major inputs/outputs of a facility's operation throughout the specified test period. This test shall consist of at least one complete production cycle after the facility has completed one or more production cycles at design operating conditions. Those inputs to be measured are fuel, electrical power, feedstock, process water, in-process chemicals (including enzymes/yeasts), and make-up water used for heating/cooling. The outputs to be measured are fuel ethanol, any applicable recoverable feedstock co-products such as distiller's grains, and waste process water. The necessary measurements, recommended methods, and calculations to quantify the four parameters are as follows:

6.2 *Conversion Efficiency*—Using the manufacturer's specified feedstock, determine whether the feedstock is classified as starch based or sugar based using Table 2. If the feedstock is a mixture, use the calculation procedures for a combination starch/sugar based feedstock. The method for analysis of moisture and starch/sugar content for starch, sugar, and combination starch/sugar based feedstocks is specified in Table 3. Table 4 details the method for calculation of the theoretical alcohol yield for each feedstock classification. The conversion factors are the stoichiometric molecular weight equivalents for conversion of a starch/sugar into ethyl alcohol. The actual yield shall be measured and adjusted to moisture-free ethanol equivalents. The proof of the alcohol shall be determined using hydrometers that conform to Specification E 100. The ratio of actual to theoretical yield represents the conversion efficiency for the process.

6.3 *Energy for Conversion*—These parameters (electrical, thermal, and total) are a function of the proof of the ethanol produced. These are represented as a ratio of the electrical, thermal, and total energy input to the fuel ethanol volumetric output. Total energy input shall be the sum of the measured electrical power consumed plus the fuel input. Electrical energy input is converted to a Btu basis using a factor of 10 000 Btu/kWh, that is derived from the theoretical conversion factor of 3412 Btu/kWh and a typical power plant efficiency of 33 %.

TABLE 2 Classification of Feedstocks

Starch Based Feedstocks	Sugar Based Feedstocks
Corn	Sugar beets
Wheat	Sugar cane
Grain sorghum	Sweet sorghum
Potatoes	Ripe fruits
Jerusalem artichokes	Whey
Milo	
Rice	
Rye	
Oats	
Barley	
Yams	

TABLE 3 Methods for Analysis of Feedstocks

Starch Based Feedstocks	
Moisture content	AOAC 14.062
Starch content	AOAC 14.073–14.074
Sugar Based Feedstocks	
Moisture content	AOAC 31.005–31.008
Glucose content	AOAC 31.051
Fructose content	AOAC 31.056
Maltose content	AOAC 31.060
Lactose content	AOAC 31.062
Combination Sugar/Starch Based Feedstocks	
Moisture content	Average value from AOAC 14.062 and AOAC 31.005–31.008
Starch content	AOAC 14.073–14.074
Glucose content	AOAC 31.051
Fructose content	AOAC 31.056
Maltose content	AOAC 31.060
Lactose content	AOAC 31.062

TABLE 4 Calculation of Theoretical Yield

Starch Based Feedstocks

$Y_T = F_D \times$ (starch content) $\times$ 0.568

Y_T = Sugar Based Feedstocks

(glucose content) $\times$ 0.511
+ (fructose content) $\times$ 0.511
+ (maltose content) $\times$ 0.538
+ (lactose content) $\times$ 0.538

Combination Sugar/Starch Based Feedstocks

Y_T = (glucose content) $\times$ 0.511
+ (fructose content) $\times$ 0.511
+ (maltose content) $\times$ 0.538
+ (lactose content) $\times$ 0.538
+ (starch content) $\times$ 0.568

where:
Y_T = theoretical alcohol yield, lb anhydrous/lb of dry feedstock
Examples:
starch based − corn at 60 % starch dry basis
$Y_T = 0.6 \times 0.568 = 0.341$ lb anhydrous alcohol/lb dry corn

Fuel input shall be expressed as dry fuel rate × lower heating value/unit measure.[10] Recommended tests for heat value of fuel are Test Methods D 1826, D 2382, D 3286, E 711, and E 870. Fuel ethanol output is the production quantity measured as moisture-free fuel ethanol during the cycle time.

6.4 *Production Rate*—This relationship shall be expressed as the total measured fuel ethanol volumetric yield (in moisture-free fuel ethanol equivalents) divided by the cycle time in hours.

6.5 *Mass Balance*—Performance according to this parameter shall be expressed as the mass ratio of outputs to inputs during the cycle time. Input is feedstock. Feedstock mass shall be calculated by quantity measurement corrected for percent moisture by the appropriate AOAC test specified in Table 3. Process water quantity shall be determined with Test Method D 2458. Process water quantity must be determined using SM 206 B, 209 C, and 507 recorded while not represented in the calculations, is a necessary measurement. Outputs are fuel ethanol and co-products (or equivalent). Mass quantities of fuel ethanol shall be expressed as moisture-free ethanol. Distiller's grains are a measured quantity with adjustments for moisture content. AOAC Test 10.231 shall be used for these adjustments. Quantitative analysis shall be determined with Test Method D 3590. Process wastewater is a measured quantity according to Test Method D 2458, while not being represented in the calculations. The quality of the process wastewater shall be determined using SM 206 B, 209 C, and 507. The quantity of recycled spent process water (backset) is measured in accordance with Test Method D 2458. In some situations, it may not be possible to obtain the mass of the solid co-products and consequently compute the mass balance. The computation for mass balance can be used to estimate the mass of the solid co-products by assuming no system losses. Such a computation may be required to estimate the mass of the solid co-products for economic analyses.

[10] The lower heating value is used to account for losses due to noncondensed water vapor in the products of combustion.

7. Calculation

7.1 *Format for Reporting Data*—As described in 4.1, an alcohol plant's performance is a function of proof. There shall be a set of data that forms a profile for that proof. Each cycle of operation during the test shall generate data that can be reported.

7.2 *Data Collection*—See Table 1.

7.3 *Data Calculations*—See Table 5.

7.4 *Data Summary*—See Table 6.

8. Precision and Bias

8.1 The precision and bias of this test method are still under evaluation.

9. Keywords

9.1 alcohol; biomass; biotechnology; ethanol; fermentation; fuel; performance

TABLE 5 Performance Calculation Procedures

		Calculation	Results
(*1*)Conversion efficiency	=	(TAY × 100)/TTY	______ lb
TTY	=	$F_A \times (1 - (M_F/100)) \times Y_T$	______ lb
TAY	=	$A_A \times (Pr/200) \times (6.625\ lb/gal)$	______ lb
(*2*)Total energy for production	=	(EEP × 10 000) + TEP	______ Btu/gal
Electrical energy for production (EEP)	=	$E_I/(A_A \times (P_r/200))$	______ k Wh/gal
Thermal energy for production (TEP)	=	$F_I/(A_A \times (P_r/200))$	______ Btu/gal
(*3*)Production rate	=	$(A_A/t_c) \times (Pr/200)$	______ Gal/h, anhydrous equivalent
(*4*)Mass balances:			
Total feedstock input (TFI)	=	$F_A \times (1 - (M_F/100))$	______ lb
Alcohol recovery	=	TAY/TFI	______ lb/lb
Distiller' grain recovery	=	$(D_G \times (1 - 100))$/TFI	______ lb/lb
Other co-product recovery (thin stillage)	=	Cpm (1 − (Mcp/100))/TFI	______ lb/lb
CO_2 production	=	(alcohol recovery × 0.9565)/M_F	______ lb/lb
Water	=	$(1 - (M_F))$	______ lb/lb
Total ______ lb/lb			

where:

A_A	=	actual alcohol product recovered during cycle, gal (60°F)
D_G	=	distillers grains, lb (wet basis)
EEP	=	electrical energy for production, kWh/gal
E_I	=	electrical energy input to process, kWh/cycle
F_A	=	measured feedstock used, lb (wet basis)
F_I	=	fuel consumed for thermal energy, units/cycle
F_Y	=	fuel lower heating value, Btu/unit
M_F	=	moisture in feedstock, wt %
M_{DG}	=	moisture in distillers grains, wt %
Pr	=	proof of alcohol (60°F)
TAY	=	total actual yield, lb of anhydrous alcohol
TEP	=	thermal energy for production, Btu/gal
TTY	=	total theoretical yield, lb of anhydrous alcohol
t_c	=	cycle time, h
Y_T	=	theoretical alcohol product yield, lb anhydrous per unit of dry feedstock
Cpm	=	co-product mass, lb
Mcp	=	moisture in co-product, wt %

Sample calculation: assume:

A_A = 20 000 gal Alc at 188 Pr 60°F
corn at 50#/Bu, 10 % protein, 8 % H_2O
60 % starch (dry basis)
bushels = 8175
cycle time = 215.7 h = t_c
kWh/cycle = 33 000

(*1*) Conversion efficiency

TTY = (8175 × 58) × (1 − 8/100) × (0.0341) = 148 663

F_A = 8175 Bu × 58#/Bu
M_F = 8 wt%
Y_T = (60/100) × 0.0568 = 0.341

TAY = 20 000 × (188/200) × 6.625 = 124 550 lb
Conversion efficiency = (124 550 × 100)/148 663 = 83.78 %

(*2*) Energy

EEP = 30 000/(20 000 × (188/200)) = 1.596 kWh/gal

kWh/cycle = 33 000
fuel = 250 000 lb
lower H.V. = 2000 Btu/lb, dry basis
moist = 30 wt %

TEP = 250 000 × (1 − 0.3) × (2000)/(20 000 × (188/200)) = 18 617
Total energy for production = (1.596 × 10 000) + 18 617 = 34 577

(*3*) Production rate = (20 000/215.7) × (188/200) = 87.16 gal/h

(*4*) Mass balance

TFI = (8175 × 58) × (1 − (8/100) = 436 218 lb
Alcohol rec = 124 550/436 218 = 0.2855 lb/lb (2.50 gal/bu)
Wet spent grain = 10^6 ton at 55 % moisture
DDG = ((10^6 × 2000#/T) × (1 − (55/100)))/436 218 = 0.2187 lb/lb (12.7 dry#/Bu)
CO_2 = (0.2855 × 0.9565)/(8/100) = 0.2731 lb/lb
Water = 1 − (8/100) = 0.0879 lb/lb
Total = 0.8643 lb/lb feed

TABLE 6 Data Summary Form for Fuel Ethanol Plant Performance Evaluation

Conversion efficiency	
Highest value	________
Lowest value	________
Average value	________
Energy for conversion	
Highest value	________
Lowest value	________
Average value	________
Production rate	
Highest value	________
Lowest value	________
Average value	________
Mass balance	
Highest value	________
Lowest value	________
Average value	________