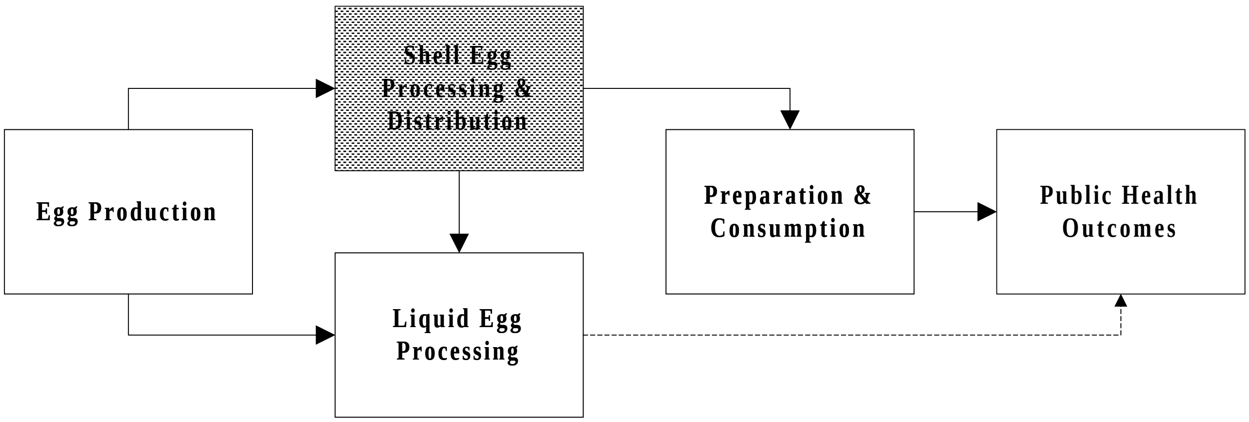
Shell Eggs Processing and Distribution Module



A. Summary of Shell Eggs Processing and Distribution Module

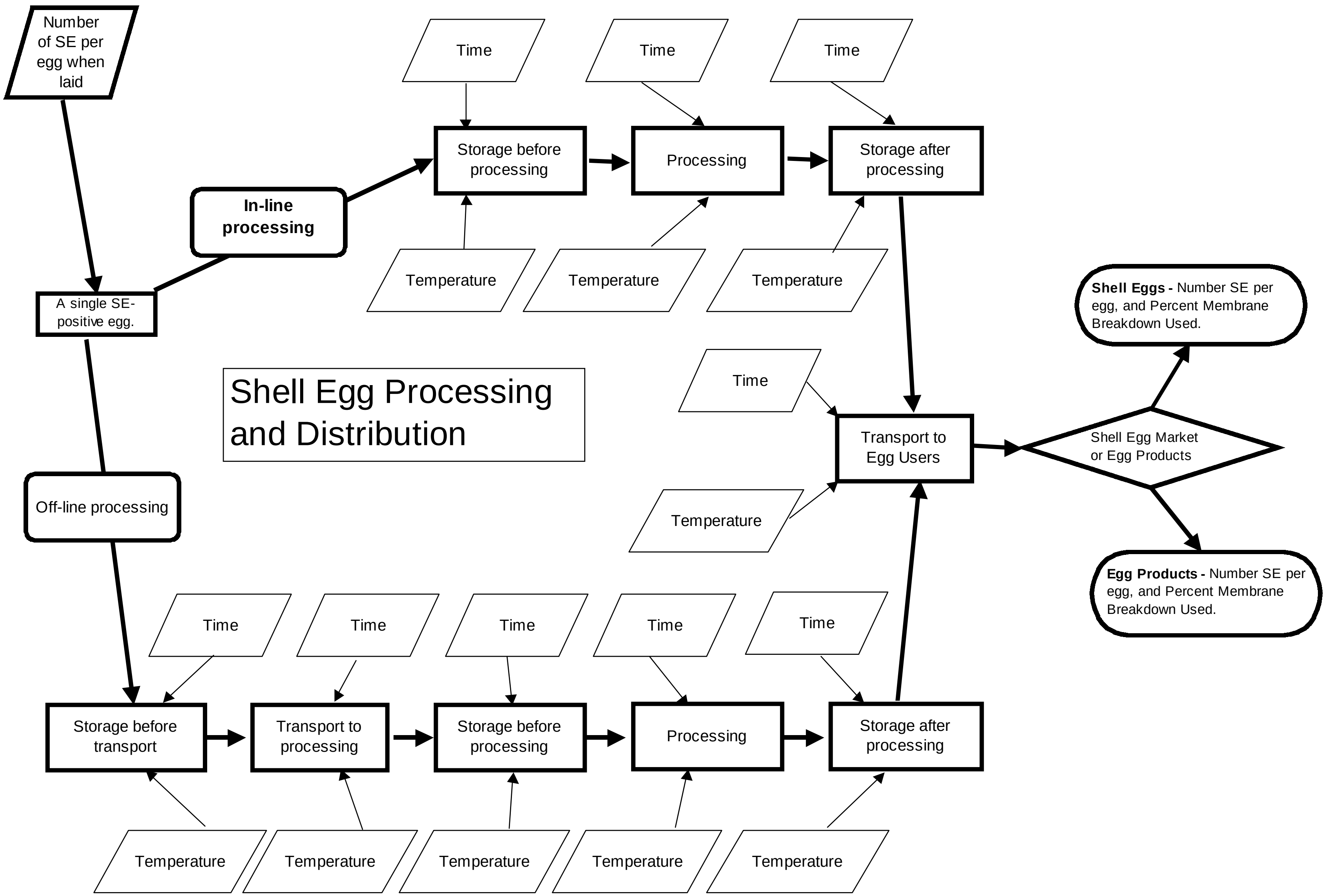
The purpose of the shell egg processing and distribution module is to simulate the processing, storage, and distribution of shell eggs from the farm to egg products processing/distribution, or preparation and consumption. Eggs remain intact throughout this process. Therefore, the primary factors affecting SE are the cumulative effects of temperatures and times of the various processing, transportation, and storage stages. The two important modeling components in this module are the time until the yolk membrane loses its integrity, and the growth rate of SE in eggs. These components are dependent on the distributions for time and temperature for various stages. The assumption is made that there is no die-off of SE once it has been deposited inside the egg.

The shell egg processing and distribution module is the next stage, following egg production, in a farm-to-table quantitative risk assessment. While the egg production module simulates the number of SE-positive eggs produced by a population of commercial flocks, this processing and distribution module calculates the likelihood of various numbers of SE bacteria for a single SE-positive egg.

An egg in this module can either follow an in-line or off-line process. An off-line processed egg is subjected to additional transportation and storage stages relative to an in-line processed egg. For either process, an egg is washed, graded, candled, and stored at the egg processing plant. An egg is then transported to either the shell egg market or to the egg products market.

At each stage of this module, time and temperature variables are used to determine the yolk membrane breakdown time of the egg. Yolk membrane breakdown time measures the time (in days) necessary before the antibacterial properties of the egg are compromised, thereby allowing replication of SE bacteria within the egg. For a stored egg, the temperature at any time is calculated from the beginning internal temperature of the egg, the ambient air temperature, and the type of packaging and environment that the egg is in. The extent of yolk membrane breakdown time is calculated as a function of temperature. The number of days in storage is then compared with the calculated membrane breakdown time to determine the percent of membrane breakdown time remaining for a specific egg. Once this percentage reaches zero, SE growth in the egg is calculated based on the time remaining and temperatures, in storage.

Salmonella on the surface of the shell is not represented in this module. The possibility of *Salmonella*, including *S*. Enteritidis migrating from the shell surface at the time of lay through the shell and two shell membranes was considered. In his review, Humphrey (1994) states that organisms die rapidly on the egg shell unless the egg is stored in high humidity and low temperatures. Little data exist on the prevalence of egg shell contamination or migration. Schoeni et al. (1995) and Chen et al. (1996) demonstrated that penetration is possible. However, if outbreaks of Salmonellosis originated from external shell contamination, outbreaks in undercooked egg products from non-Enteritidis strains would be frequent. Epidemiologic data does not indicate this occurs (Tauxe, 1997) and outbreaks are predominantly *S*. Enteritidis. Therefore, this risk assessment will consider only *S*. Enteritidis which are inside the freshly-laid egg.


Shell Egg Processing and Distribution
Number of SE per egg when laid
A single SE-positive egg.
In-line processing
Off-line processing
Time
Storage before processing
Temperature
Time
Processing
Temperature
Time
Storage after processing
Temperature
Time
Transport to Egg Users
Temperature
Shell Egg Market or Egg Products
Shell Eggs - Number SE per egg, and Percent Membrane Breakdown Used.
Egg Products - Number SE per egg, and Percent Membrane Breakdown Used.
Time
Storage before transport
Temperature
Time
Transport to processing
Temperature
Time
Storage before processing
Temperature
Time
Processing
Temperature
Time
Storage after processing
Temperature

B. Inputs to the Shell Egg Module

1. Number of SE bacteria per positive egg at lay

The number of SE bacteria per positive egg at lay variable is used to calculate growth of SE once an egg's membrane breakdown is complete. Until then, the number of SE bacteria is modeled as unchanged through the different stages of the shell egg processing and distribution module. The assumption is made that there is no die-off of SE once it has been deposited inside the egg.

a. Evidence

Table B-1. Evidence for the number of SE organisms per egg at lay

Reference	**Mean[2]**	**min.**	**mode**	**max.**
Gast and Beard[1], 1992 **(Artificially infected hens)**	200	60	180	420
Humphrey et al., 1991 **(naturally infected hens)**	7	1	5	20

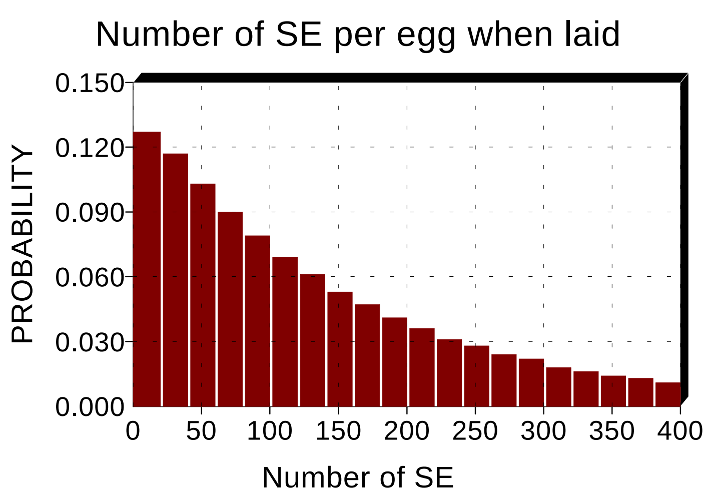
[1] Values are extrapolated from published values based on 60 ml per egg.
[2] The mean value is the calculated expected value of a Pert(min, mode, max) distribution.

b. Mean – 122 SE bacteria

c. Distribution – Truncated Exponential (152,1,400)

This distribution incorporates the high levels of SE fond by Gast and Beard with artificially infected hens while allowing for the low values found by Humphrey in naturally infected hens. This distribution also attempts to include the growth of SE up to 1 log that can occur initially after laying before the pH increases (Humphrey, 1993).

Figure B-2



C. Shell Egg Module Variables

1. Probability that an egg is processed in-line

The probability of an egg being processed at an in-line facility is used in this module to determine whether an egg avoids transportation from the farm to a processing facility. The probability that an egg is processed off-line – thereby subjected to additional time in storage and transportation prior to processing – is equal to (1- p) where p is the probability of an egg processed in-line. Other egg handling scenarios such as cryogenic cooling are possible but occur in low frequencies in the U.S. They can be incorporated into the model for comparison purposes or for testing mitigation strategies.

a. Evidence –

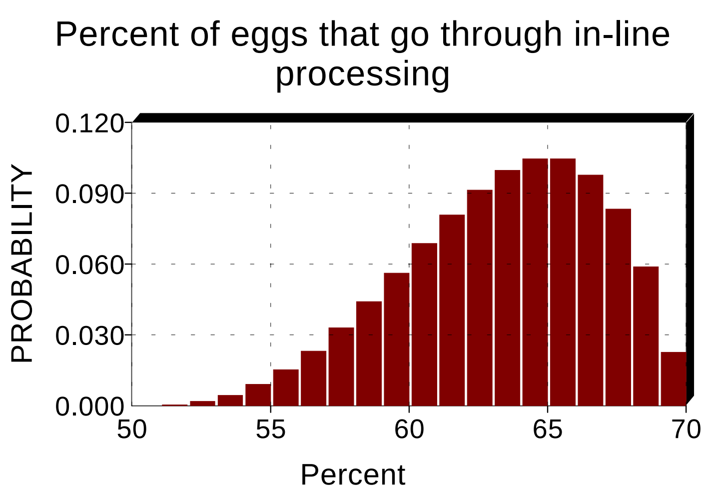
Personal communication Dr. P. Curtis, NC State University.

b. Mean – 0.63

c. Distribution – Pert(0.50,0.65,0.70)

This distribution reflects the survey and experience with the egg industry in the Southeast. In the past, over half of the eggs went to in-line processing and the new and larger facilities being constructed are usually in-line. This mean represents an estimate of the current ratio.

Figure B-3



Shell Egg Processing and Distribution Module

Time and temperature for processing and transport

Time and temperature variables are used in the shell egg processing and distribution module at the following stages;

- pre-processing storage/transportation for off-line processed eggs,

- storage at processing (for in-line or off-line eggs),

- storage during transport to shell egg markets or egg products processors.

At each stage of this module, time and temperature variables are used to calculate the yolk membrane breakdown time, percent membrane breakdown time remaining, and growth of SE in an egg. Time and temperature for each stage are independent, but these variables' distributions are basically similar.

The distributions for time and temperature in storage or transport are developed based on studies by Anderson et al. (1992), Bell & Curley (1966), Czarick and Savage (1992), and Stadelman & Rhorer, 1987.

Off-line processing

Eggs are collected on farms, where some eggs may also be washed, and stored in 13-16 C (55-60° F) pre-processing cooler. Internal eggs temperature declines from 37 to 20° C (99 to 68° F).

Eggs are transported to processors at a mean ambient temperature of 59.2° C (45-90° F)

Eggs arrive at processor at 16-20° C (60-68° F).

Washing-candling raise temperatures to 24-27° C (76-80° F) internal temperature followed by an increase of 2° C (5-6° F) in first 6 hours if palletized in processing room (processing room 22-28° C (72-82° F)). Post processing coolers were 7- 13° C (45 - 55° F), palletized eggs declined to 18° C (65° F) in 50 hours and to 14° C (57° F) in 100 hours (Anderson et al., 1992).

2. Storage temperature before transportation for off-line eggs (F)

   a. Evidence –

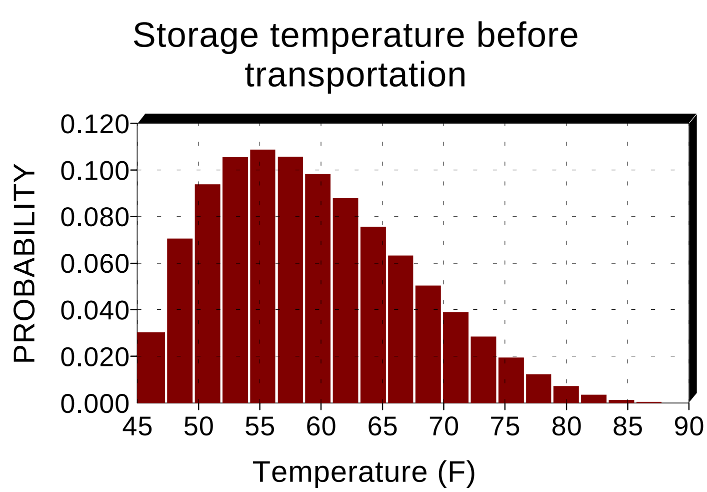
      Eggs decline in temperature after lay from 99 to 68° F. Eggs arrive at processor at 60-68° F (Anderson et al.,1992). Personal communication from egg industry (UEP, Atlanta, 1998).

   b. Mean – 59° F.

   c. Distribution – Pert(45,55,90)

      Evidence suggests it most likely that eggs stored prior to off-line processing will be kept at room temperature. Some eggs may be refrigerated at ambient temperatures as low as 45° F. A few eggs may remain at ambient temperatures as high as 90° F.

Figure B-4



3. Storage time before transportation for off-line eggs (hours)

a. Evidence –

Eggs are collected on farms, where some eggs may also be washed, and stored 0.5 to 7 days before transportation from the farm to an off-line processing facility (Anderson et al.,1992). Personal communication from egg industry (UEP, Atlanta, 1998).

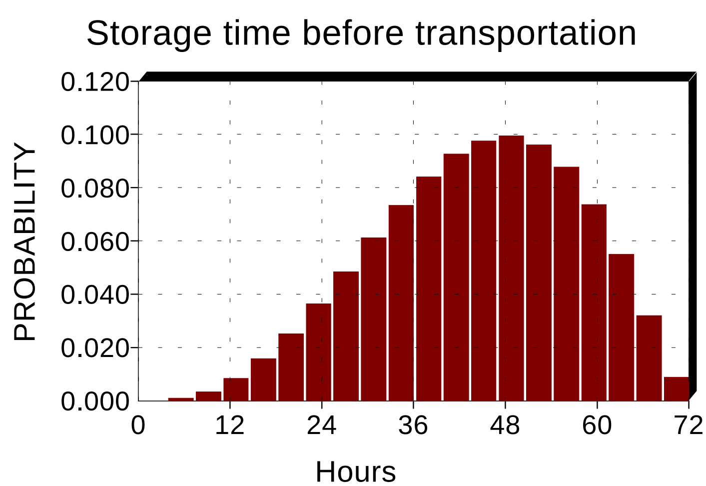
b. Value – 44 hours

c. Distribution – Pert(1, 48, 72)

Some eggs may be transported within 1 hour of being laid. However, some houses may have pickups only every 2 days. It would be possible in this case to have an egg that stays in the house 3 days before transporting. Therefore, this relatively broad distribution has the most frequent time for eggs to reach the processor as 48 hours.

Cooling rate for before transportation has a mean k parameter of 0.08 for eggs in individual flats (boxes) or plastic baskets. Pert(0.0053,0.08,0.107)

Figure B-5



4. Ambient temperature during transportation of off-line eggs (F)

   a. Evidence –

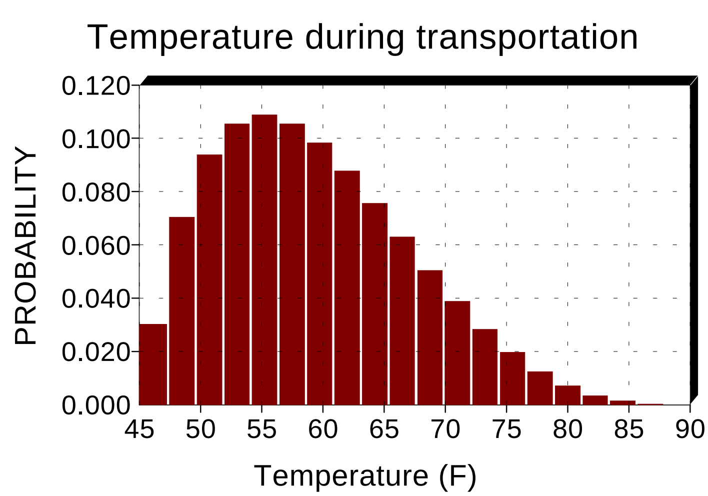
      Personal communication from egg industry (UEP, Atlanta, 1998).

   b. Mean – 59° F

   c. Distribution – Pert(45,55,90)

      Current information suggests that the ambient temperature of eggs transported from the farm to an off-line processor encompasses a wide range. The lowest possible ambient temperature is modeled as 45° F and the most likely ambient temperature is 55° F. Despite widespread refrigeration it is assumed that the highest ambient air temperature during transportation is 90° F.

Figure B-6



5. Time for transportation for off-line eggs (hours)

a. Evidence –

Personal communication from egg industry (UEP, Atlanta, 1998).

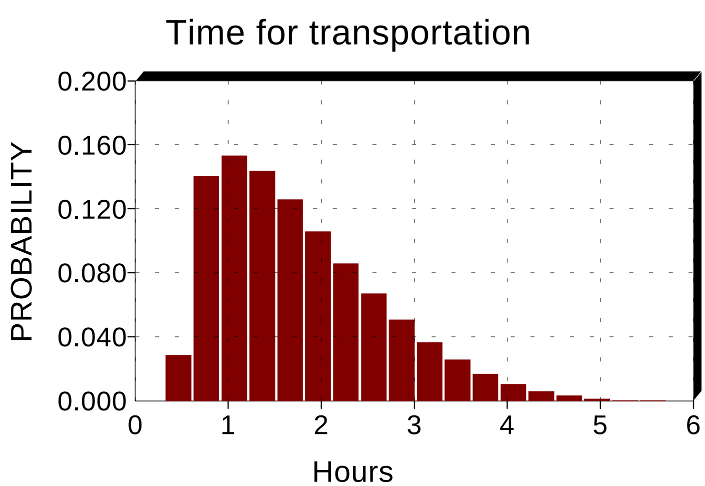
b. Mean – 1.8 hours

c. Distribution – Pert(0.5,1,6)

According to personal communication from UEP, all off-line processed eggs will take no more than 6 hours to get to a processing facility, with the minimum amount of time to be 0.5 hour and the most likely value to be 1 hour.

Cooling rate parameter for eggs during transportation is k = 0.25 for eggs in individual boxes. However, the range is relatively broad to reflect the differences in packaging, air circulation rates and other factors during this stage, Pert(0.0165,0.25,0.335) .

Figure B-7



6. Storage temperature before processing at off-line processor (F)

a. Evidence –

Personal communication from egg industry (UEP, Atlanta, 1998).

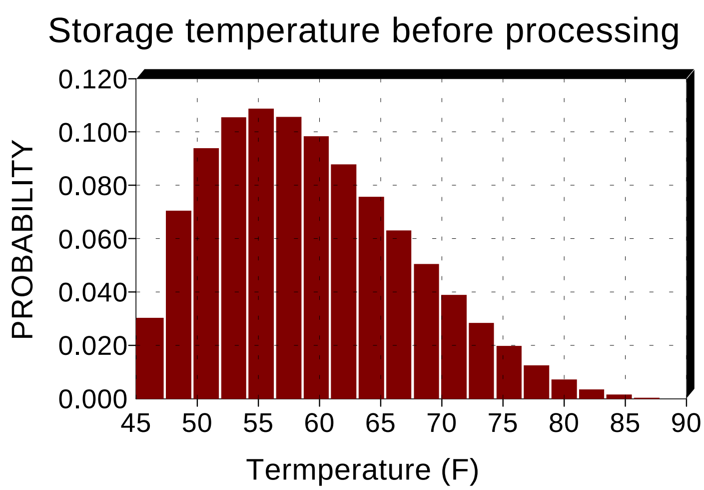
b. Mean – 59° F.

c. Distribution – Pert(45, 55, 90)

The ambient temperature of storage at an off-line processor prior to processing may encompass a wide range.

The lowest possible ambient temperature is modeled as 45° F., and the most likely ambient temperature is 55° F., however, the highest possible ambient temperature is 90° F.

Figure B-8



7. Storage time before processing at off-line processor (hours)

   a. Evidence –

   Personal communication from egg industry (UEP, Atlanta, 1998).

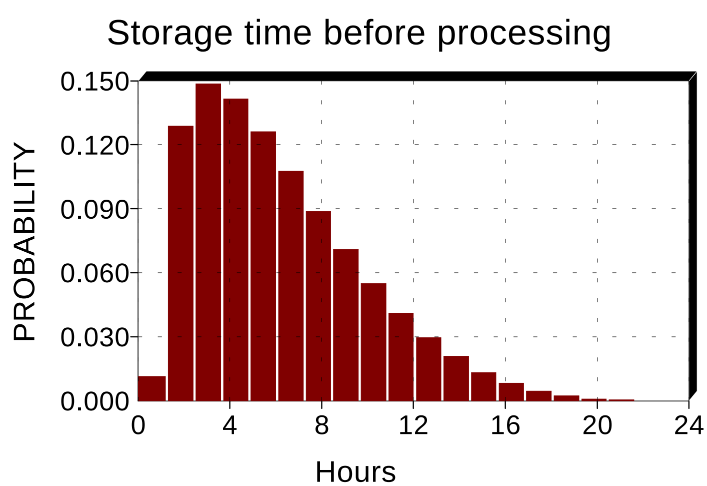
   b. Mean – 6 hours

   c. Distribution – Pert(1,3,24)

   Available information suggests off-line processed eggs will seldom be stored longer than 24 hours at an off-line facility before processing. The minimum storage time is 1 hour and the most likely time is 3 hours.

   Cooling rate parameter for before processing is k = 0.08 for eggs in individual flats (boxes). Pert(0.0053,0.08,0.107)

Figure B-9



Shell Egg Processing and Distribution Module

8. Ambient temperature at processing at off-line processor (F)

   a. Evidence –

      Personal communication from egg industry (UEP, Atlanta, 1998). Washing and candling of eggs at processing raises temperatures to 76-80° F internal temperature (Anderson et al., 1992).

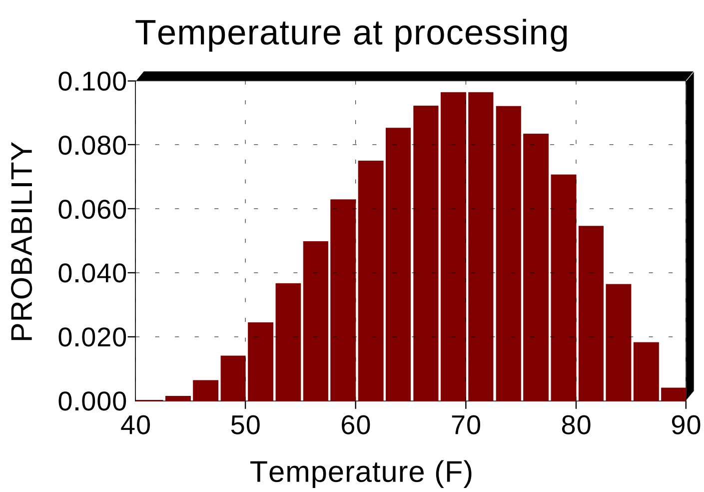
   b. Mean – 69° F.

   c. Distribution – Pert(41,70,90)

      Available information suggests that the ambient temperature for eggs during processing encompasses a wide range. The lowest possible ambient temperature is modeled as 41° F., the most likely ambient temperature is 70° F., and the highest possible ambient temperature is 90° F.

      The egg temperature begins this phase with a 10 degree F increase described as Normal(10,1).

Figure B-10



9. Time for processing at off-line processor (hours)

   a. Evidence –

      Personal communication from egg industry (UEP, Atlanta, 1998).

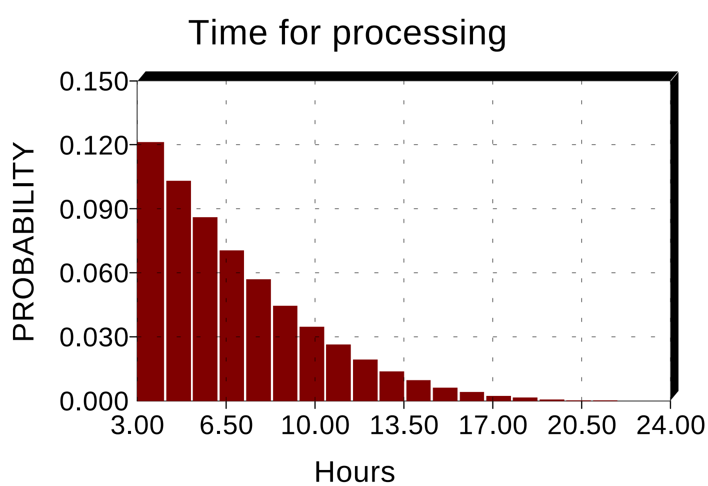
   b. Mean – 4.7 hours

   c. Distribution – Pert(0.5, 1, 24)

      Available information suggests the time for actual processing of eggs will normally be 1 hour and no less than ½ hour. Times may extend up to 24 hours. Processing includes all the time between removing the eggs from storage until they are placed back into storage.

      Cooling rate parameter for processing is k = 0.50 for eggs that are individually exposed to air and water. Pert(0.033,0.50,0.67)

Figure B-11



10. Storage temperature after processing at off-line processor (F)

   a. Evidence –

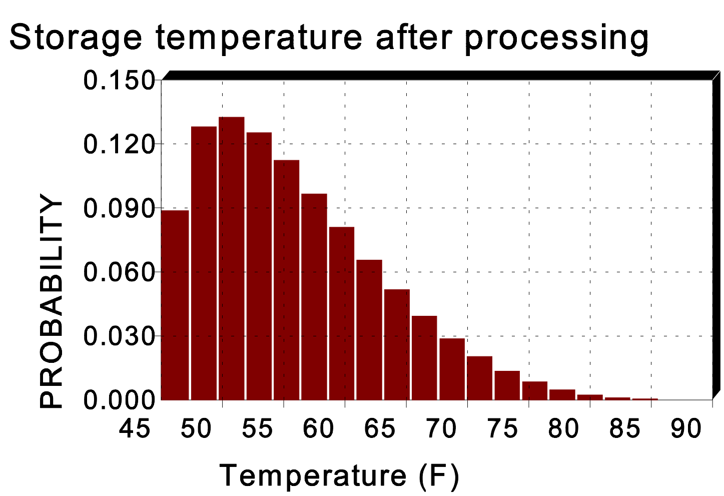
   Personal communication from egg industry (UEP, Atlanta, 1998).

   b. Mean – 56° F.

   c. Distribution – Pert(45,50,90)

   Available information suggests the ambient temperature of eggs after processing while in storage at an off-line processor is usually refrigerated, but temperatures encompass a wide range. The lowest possible ambient temperature is modeled as 45° F., the most likely ambient temperature is 50° F., and the highest possible ambient temperature is 90° F.

Figure B-12



11. Storage time after processing at off-line processor (hours)

a. Evidence –

Personal communication from egg industry (UEP, Atlanta, 1998).

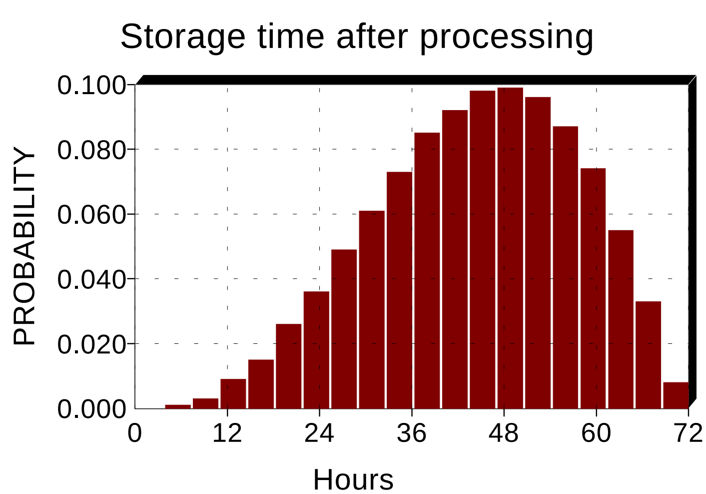
b. Mean – 44 hours

c. Distribution – Pert(1,48,72)

Available information suggests off-line processed eggs will seldom be stored longer than 72 hours after processing. The minimum storage time is 1 hour and the most likely time is 48 hours.

Cooling rate parameter after processing is k = 0.008 Pert(0.0005,0.008,0.0107) for eggs in the interior of flats that are stacked in pallets.

Figure B-13



Shell Egg Processing and Distribution Module

In-line processing

Eggs are conveyed from the laying house directly to the processing area where they are washed, candled, cartoned or cased, palletized, and placed under refrigeration. Cooling data (from figure 4 in Anderson et al., 1992). Eggs leave washing at 27-34° C (80-94° F) and cool to 27° C (80° F) internal temperature in 48 hours in a 10° C (50° F) cooler.

12. Ambient storage temperature before processing at in-line processor (F)

a. Evidence –

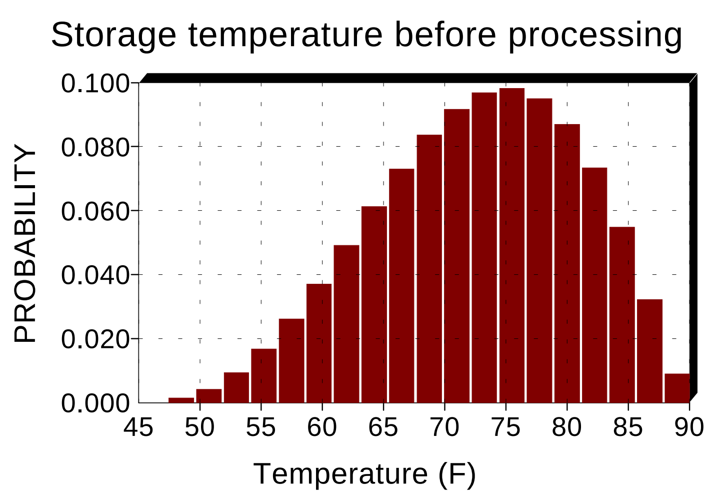
Personal communication from egg industry (UEP, Atlanta, 1998).

b. Mean – 73° F.

c. Distribution – Pert(45,75,90)

Available information suggests that the ambient temperature of eggs prior to processing while in storage at an in-line processor encompasses a wide range. The lowest possible ambient temperature is modeled as 45° F., the most likely ambient temperature is 75° F., and the highest possible ambient temperature is 90° F.

Figure B-14



13. Storage time before processing at in-line processor (hours)

a. Evidence –

Personal communication from egg industry (UEP, Atlanta, 1998).

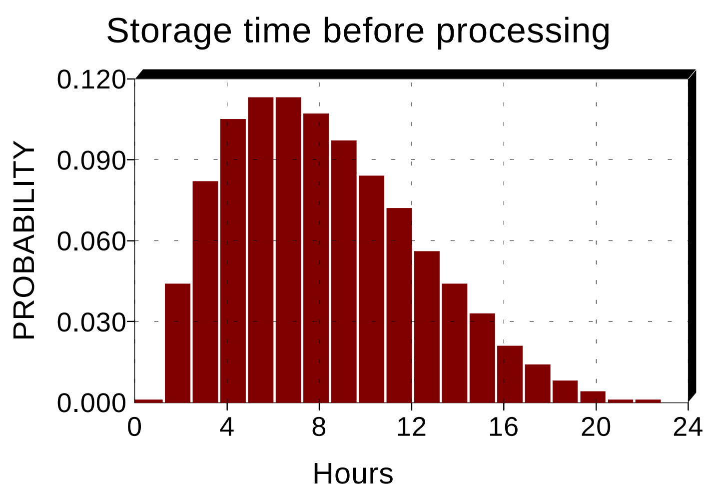
b. Mean – 8 hours

c. Distribution – Pert(1,6,24)

Available information suggests all in-line processed eggs will be stored no longer than 24 hours at an in-line facility before processing. The minimum storage time is 1 hour and the most likely time is 6 hours.

Cooling rate parameter before processing is k = 0.08 for eggs in individual boxes. Pert(0.0053,0.08,0.107).

Figure B-15



Shell Egg Processing and Distribution Module

14. Ambient temperature during processing at in-line processor (F)

a. Evidence –

Personal communication from egg industry (UEP, Atlanta, 1998). Washing and candling of eggs at processing raises temperatures to 76-80°F internal temperature (Anderson et al., 1992).

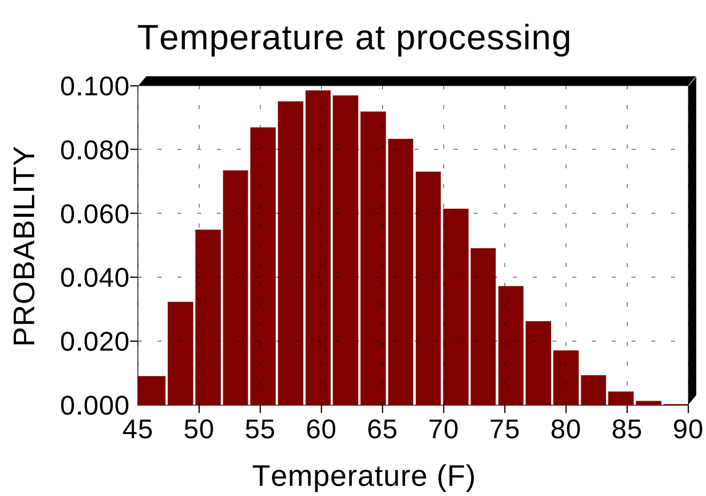
b. Mean – 63° F.

c. Distribution – Pert(45,60,90)

Available information suggests that the ambient temperature for eggs during processing encompasses a wide range. The lowest possible ambient temperature is modeled as 45° F., the most likely ambient temperature is 60° F., and the highest possible ambient temperature is 90° F.

The egg temperature begins this phase with an 8 degree Fahrenheit increase described as Normal(8,1).

Figure B-16



15. Time for processing at in-line processor (hours)

a. Evidence –

Personal communication from egg industry (UEP, Atlanta, 1998).

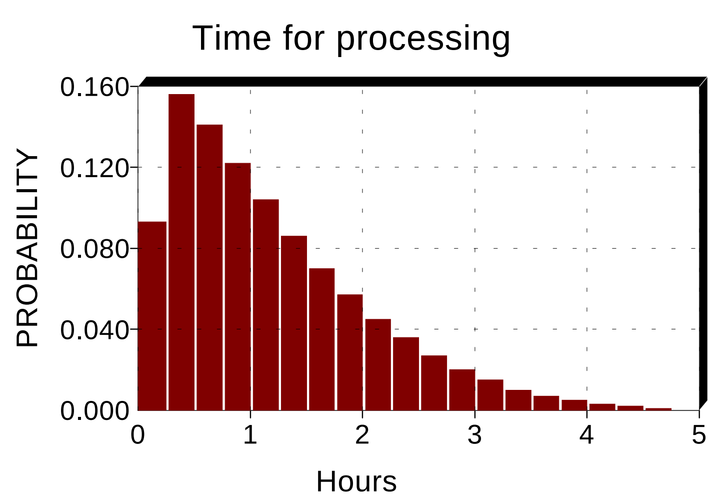
b. Mean – 1.2 hours

c. Distribution – Pert(0.1, 0.25, 6)

Available information suggests the time for actual processing of eggs is seldom more than 6 and no less than 0.1 hour. Processing includes all the time between removing the eggs from storage until they are placed back into storage.

Cooling rate parameter for processing is k = 0.50 Pert(0.033,0.50,0.67) for individual eggs.

Figure B-17



16. Ambient storage temperature after processing at in-line processor (F)

a. Evidence –

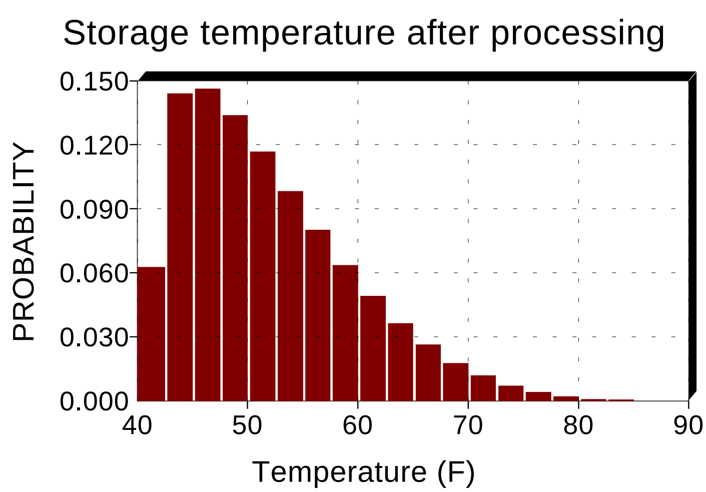
Personal communication from egg industry (UEP, Atlanta, 1998).

b. Mean – 52° F.

c. Distribution – Pert(41,45,90)

Available information suggests that the ambient temperature of eggs after processing while in storage at an in-line processor encompasses a wide range. The lowest possible ambient temperature is modeled as 41° F., the most likely ambient temperature is 45° F., and the highest possible ambient temperature is 90° F.

Figure B-18



Shell Egg Processing and Distribution Module

17. Storage time after processing at in-line processor (hours)

    a. Evidence –

       Personal communication from egg industry (UEP, Atlanta, 1998).

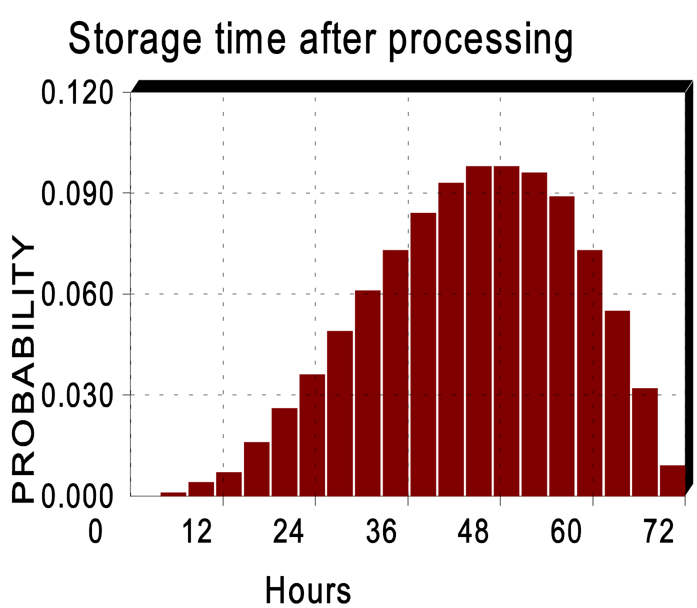
    b. Mean – 44 hours

    c. Distribution – Pert(1,48,72)

       Available information suggests all off-line processed eggs will be stored no longer than 72 hours at an in-line facility after processing. The minimum storage time is 1 hour and the most likely time is 48 hours.

       Cooling rate parameter for after processing is k = 0.008 for eggs in the interior of boxes and stacked pallets. Pert(0.0005,0.008,0.0107)

Figure B-19



Transportation to Egg Users

18. Transportation temperature

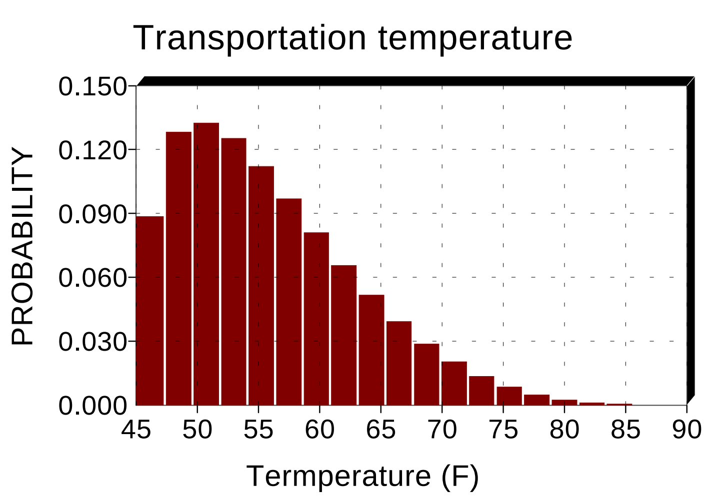
   a. Evidence –

      None

   b. Mean – 56° F.

   c. Distribution – Pert(45,50,90)

Figure B-20



Shell Egg Processing and Distribution Module

19. Transportation time

a. Evidence –

None

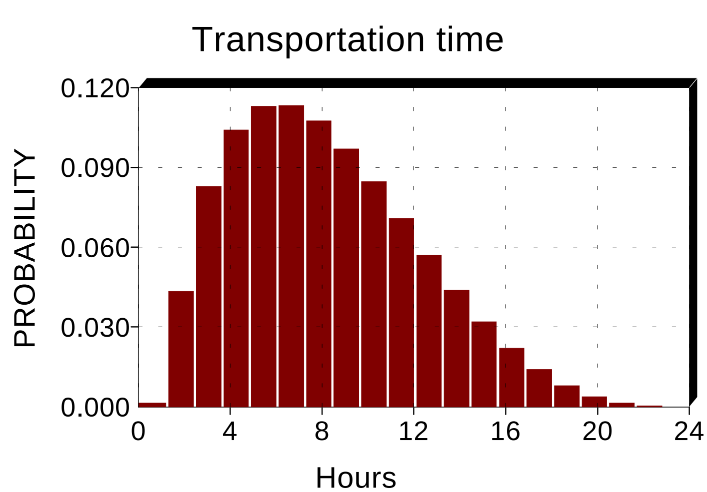
b. Mean – 8 hours

c. Distribution – Pert(1,6,24)

Egg production is regional and truck transportation has eggs reaching their markets within 24 hours.

Cooling rate parameter for transportation is k = 0.32 for eggs in individual boxes. However, the range is relatively broad to reflect the differences in packaging, air circulation rates and other factors during this stage, Pert(0.0231,0.35,0.469)

Figure B-21



D. Modeling Periods and Elements

Each of the storage, processing, and transportation periods will comprise a unit composed of the three models for cooling, yolk membrane survival and *Salmonella* growth. Each period will take the internal egg temperature, fraction of yolk membrane time remaining and number of *Salmonella* from the previous unit and using the time and ambient temperature of that period calculate the internal egg temperature, fraction of yolk membrane time and *Salmonella* numbers that are passed on to the next period.

Model Elements

1. Cooling of eggs

The interactions of initial egg internal temperature, air temperature, packaging and other variables on the temperature cooling is modeled by a simplified non-steady state heat transfer. The relationship is

$$\log [(T - T_o)/(T_i - T_o)] = -kt$$

where T is the temperature (F) at a specific time t (hours) in the interior of the egg (i.e. center egg within box or pallet), Ti is the initial egg temperature at the beginning of the cooling period and To is the air temperature. The estimated temperature (T) is the internal temperature of an egg in the center of the box or pallet. This assigns to all eggs in the pallet the temperature of the warmest egg in the pallet, which is thought to be in the center of the pallet. This assumption overestimates the temperature of most eggs in the pallet and provides a conservative (i.e. over estimate) of the risk of SE growth.

The parameter k depends on the combination of thermal characteristics of the egg, packaging and air circulation around the packaging.

Values for k were determined by fitting this equation to published graphs showing egg cooling. The following table lists these fits.

Table B - 3. K Values determined by fitting an equation to published egg cooling graphs

Situation	k	Reference
Pallet, cardboard & fiber flats, In-line	0.0075	Anderson et al., 1992
Pallet, cardboard boxes	0.008	Czarick & Savage, 1992
Pallet, cardboard boxes, Styrofoam	0.013	Czarick & Savage, 1992
Pallet, cardboard, Off-line	0.035	Anderson et al., 1992
Single cardboard case	0.052	Czarick & Savage, 1992
Flats, closed	0.07	Bell & Curley, 1966
Flats, folded shut	0.08 to 0.14	Bell & Curley, 1966
Pallet, plastic baskets, Styrofoam	0.11	Czarick & Savage, 1992
Open stack	0.2 to 0.4	Bell & Curley, 1966
Fiber case, foam cartons with & without slots, moving air	0.24	Stadelman & Rhorer, 1987
Open stack, forced air	0.4 to 1.0	Bell & Curley, 1966
Cryogenic cooling	11	Curtis et al., 1995

Four replicate cooling curves provided by Dr. Anderson, NC State Univ., were used to estimate the likely ranges for the k values. The mean of the ranges divided by their averages was 0.51. This value was used for all the pert distributions.

2. Yolk membrane breakdown

The yolk membrane breakdown variable is used to calculate the number of days an egg is resistant to internal SE replication at a given temperature.

Table B-3 shows the results of a study in which a group of 9-11 eggs was artificially infected with a known number of SE bacteria and was incubated at a known temperature. In a similar manner other groups of 9-11 eggs were also artificially infected with a known number of SE and were incubated at a known temperature (i.e. 12° C, 16° C, 20° C, etc.). The groups of eggs were monitored to detect the growth of SE within the artificially infected eggs being incubated at known temperatures. During the incubation period the yolk membrane begins to deteriorate at the molecular level, but appears to be normal to visual inspection. This molecular breakdown of the yolk membrane permits the nutrients within the yolk to be available to the SE for growth within the artificially infected eggs. Therefore, growth in the number of SE within the infected egg is an indicator of the breakdown of the yolk membrane at the molecular level, and this breakdown is sufficient to make the nutrients within the yolk available to the SE for growth. The time from artificial infection of the eggs with a known number of SE and incubation at a known temperature to the detection of growth of SE in 25% of the eggs within a group of 9-11 eggs is measured in days and is the time required for breakdown of the yolk membrane at a specific temperature. For example, at an incubation temperature of 12° C, growth of SE in an artificially infected group of eggs will be present in 25% of the eggs at 35 days. Similarly, at an incubation temperature of 25° C, growth of SE in an artificially infected group of eggs will be present in 25% of the eggs at 6 days. This entire set of experiments was repeated a number of times, and each replication is represented by a row in Table B-3.The data was obtained from Dr. T. Humphrey, Exeter, UK.

Table B-3. Time before growth of *S*. Enteritidis in eggs stored at various temperatures

	Temperature in degrees centigrade								
	12° C	**16° C**	**20° C**	**23° C**	**24° C**	**25° C**	**27° C**	**30° C**	**37° C**
Replicates (Days)	35*	21	17	18	7	6	6	6	3
	28	28	42		10	12	12	7	
	42	28	14		7		7	6	
	42	28	27		10		6	13	
	28		28		12				
	28		28						

*Time for more than 25% of the eggs in a group of 9-11 eggs to permit SE growth

Shell Egg Processing and Distribution Module

The logarithm of time before growth linearly decreased with increasing temperature. The fitted regression equation and 95% confidence intervals are (in days and degrees C) (Steel and Torrie, 1960):

$$\log_{10} YM =$$

$$\{(2.0872 - 0.04257\ T) \pm (2.042*0.15245)[(1/32) + ((T -21.6)\hat{}2/(32*43.2))]\hat{}0.5\}$$

At each of the stages (previously defined) of the shell egg processing/distribution module, the yolk membrane breakdown is calculated. If storage time of the egg at a particular stage is less than the yolk membrane breakdown calculated for that stage, then the percent of yolk membrane breakdown time used in that stage is calculated. This percent of yolk membrane used is cumulative from stage to stage. If the cumulative percent membrane breakdown used equals or exceeds 100% at any stage of this module, then growth of SE in that stage is calculated for the time remaining in that stage and all subsequent stages.

3. SE growth rate

The SE growth rate variable is used in this module to calculate the number of SE bacteria in an egg once yolk membrane breakdown is complete. This variable is calculated using the following linear regression equation:

$$\text{Growth rate (log(cfu/h)} = \mu = -0.143 + 0.026T$$

where μ is the square root of the growth rate, T is the internal egg temperature (^{o}C). The logs of growth in a stage of this module is calculated by multiplying the growth rate by the number of hours available for growth. The number of SE bacteria in an egg at the end of a module stage is then calculated as the cumulative number of log SE bacteria in the egg from the preceding stages.

The equation for SE growth rate was estimated using data from Bradshaw et al. (1990) and Schoeni et al. (1995).

Temperature	Generation Times (h)	
Centigrade	Bradshaw et al.	Schoeni et al.
4°		No Growth
7°	No Growth	
10°		10.3
15.5°	3.5	
25°		1.7
37°	0.41	

$$\text{SqRt EGR} = \{ (-0.1434 + 0.026012\ T) \pm (3.182)(0.02124)[(1/5)+(T -18.9)^2/(5*149.30)]\}$$

This equation calculates the mean and 95% confidence intervals (Steel and Torrie, 1960).

4. Probability of egg marketed to egg products

The probability of marketing an egg to an egg products processor is used in this module to determine the distribution of yolk membrane breakdown time and number of SE bacteria per egg for SE-positive eggs sent to breaking plants. The likelihood of an egg marketed to shell egg users (e.g., retail, institutions) is simply (1-p), where p is the probability of an egg marketed to egg products.

The distribution for this variable is developed using USDA-AMS data which shows that 4.5% of graded/processed eggs are restricted and diverted to egg products processors. Data from the Pennsylvania Pilot Project (Schlosser et al., 1995) demonstrated that blood spot eggs were more frequently SE-positive than eggs without blood spots. This study also demonstrated a similar increase in washed, dirty eggs. Therefore, the probability that an SE-positive egg is diverted is modeled as 4.5% times Pert (min, mode, max). The Pert distribution parameters are taken from the calculated odds ratio for blood spot eggs (Schlosser et al, 1995) and equals Pert (0.89, 1.79, 3.55).

Shell Egg Processing and Distribution Module

E. Results

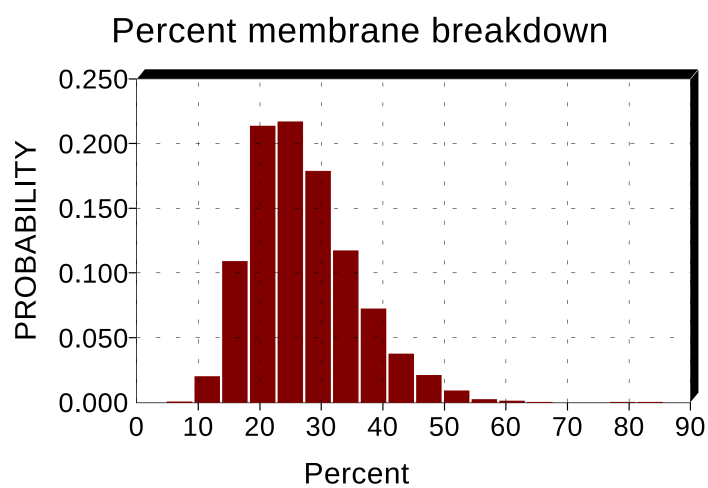
Summary

The most significant output of the Shell Egg Processing and Distribution module is the percent yolk membrane breakdown that occurs because no microbial growth occurs until membrane breakdown is complete. Membrane breakdown is a function of time and temperature. This output is summarized in the table and graph below.

Table B-5. Percent Yolk Membrane Breakdown Resulting from the Shell Egg Processing and Distribution Module

	% yolk membrane breakdown
Mean	26.9
Standard deviation	8.5
5th percentile	15.2
95th percentile	42.6

Figure B-22



F. Sensitivity Analysis

The percent yolk membrane was most sensitive to storage times and temperatures before and after processing where the variables allowed for extreme values. There was not sufficient time and temperature abuse modeled to allow for complete yolk membrane breakdown and rapid growth of bacteria. The percent yolk membrane breakdown that does occur, however, lessens the time needed for complete breakdown to occur in the preparation and consumption module.

Table B-6. Sensitivity Analysis of In-Line Processing Variables

In Line Processing Variable	Correlation Coefficient
Storage time after processing	0.46
Temperature at processing	0.315
Storage temperature before processing	0.311
Storage temperature after processing	0.134

Table B-7. Sensitivity Analysis of Off-Line Processing Variables

Off Line Processing Variables	Correlation Coefficient
Storage time after processing	0.278
Storage temperature before processing	0.198
Temperature at processing	0.177
Temperature at processing	0.172
Time for transportation	0.167
Storage time after processing	0.123
Temperature during transportation	0.104
Transportation time	0.093

G. Mathematics of the Shell Egg Processing and Distribution Module

1. Definition of subscript notation.

Shell eggs undergo processing in either an ‘in-line’ mode or in an ‘off-line’ mode. The subscript ‘i’ is used with many of the variables in the Shell Egg Processing and Distribution Module to designate whether the shell egg is being processed in either an ‘in-line’ mode or in an ‘off-line’ mode. If the value of ‘i’ is equal to 1, then the egg is being processed in an ‘in-line’ mode. If the value of ‘i’ is equal to 2, then the egg is being processed in an ‘off-line’ mode. Hence, the subscript ‘i’ may have the value of either 1 or 2.

Shell eggs may be exposed to a maximum of 6 different storage periods before sale at retail. The subscript ‘j’ is used with many of the variables in the Shell Egg Processing and Distribution Module to designate a specific storage period to which the shell egg may be exposed. The following table describes each of the values which the subscript ‘j’ may have for eggs which are processed in either an ‘in-line’ mode or in an ‘off-line’ mode.

Many of the variables in the Shell Egg Processing and Distribution Module will have both the ‘i’ and ‘j’ subscripts. The value of the ‘i’ subscript is written first, and the value of the ‘j’ subscript is written second. For example if the variable t_{ij} is written as t_{13} (or more explicitly $t_{i=1,\ j=3}$), then this indicates the time an egg undergoing in-line processing (i=1) spends in storage after processing (j=3).

	In-line processing **i = 1**	Off - line processing **i = 2**
Value of ‘j’ subscript	Description of storage period	
j = 1	Storage before processing	Storage before transportation
j = 2	Processing	transportation before processing
j = 3	Storage after processing	Storage before processing
j = 4	Transportation to retail	Processing
j = 5		Storage after processing
j = 6		Transportation to retail

2. Definition of Constants

Shell Egg Processing and Distribution Module

T_0 Initial temperature of egg = 99° F

tYM_o Initial yolk membrane integrity time used = 0

FYM_0 Initial fraction yolk membrane time used = 0

3. Input Variables

$SE_0 \equiv Log_{10}$ initial number of S. Enteritidis bacteria in an egg

$P_i \equiv$ probability of an egg being processed in-line (where i=1) or off line (where i=2)

4. Calculations

In-line process vs. off-line process:

P_1 = probability of eggs being processed in-line pert(0.50,0.65,0.70) distribution

$P_2 = (1 - P_1)$ = probability of eggs being processed off-line

Times:

t_{ij} = Time period for a step (d) = User input

tYM_o = Initial yolk membrane integrity time used = 0.0

tYM_{ij} = Yolk membrane integrity time for a step (h) = $10^{(2.0872 - 0.04258 AT_{ij})}$

tG_{ij} = Time period within step available for growth = $t_{ij} (1 - (EYM_{ij}/(t_{ij} / tYM_{ij})))$

tGS_{ij} = Time growth started = $t_{ij} - tG_{ij}$

Temperatures:

$T_{i0} = T_0$ = Initial temperature of egg = 99° F

TA_{ij} = Air temperature for a step (F) = User input

k_{ij} = Cooling parameter (h^{-1}) = User input

T_{ij} = Egg temperature at end of a step = $e^{(-k_{ij} * t_{ij})} (T_{i(j-1)} - TA_{ij}) + TA_{ij}$

Shell Egg Processing and Distribution Module

AT_{ij} = Average egg temperature of a step = $e^{((-k_{ij} * t_{ij})/2)} (T_{i(j-1)} - TA_{ij}) + TA_{ij}$

TG_{ij} = Temperature at start of growth = $e^{(-k_{ij} * tGS_{ij})} (T_{i(j-1)} - TA_{ij}) + TA_{ij}$

ATG_{ij} = Average temperature in growth period = $e^{((-k_{ij} * tGS_{ij})/2)} (T_{i(j-1)} - TG_{ij}) + TG_{ij}$

Yolk membrane integrity status - intact vs compromised:

FYM_0 = Initial fraction yolk membrane time used = 0.0

FYM_{ij} = Summed fraction yolk membrane time used = $(t_{ij}/tYM_{ij}) + FYM_{I(j-1)}$

EYM_{ij} = Excess yolk membrane fraction = $1 - FYM_{ij}$

If $FYM_{ij} < 1.0$ then EGR_{ij} = Exponential growth rate = 0.0

If $FYM_{ij} \geq 1.0$ then EYM_{ij} = Excess yolk membrane fraction = $1 - FYM_{ij}$

EGR_{ij} = Exponential growth rate = $(-0.143 + 0.026\ ATG_{ij})^2$

S. Enteritidis populations:

SE_0 = Log_{10} initial number of S. Enteritidis = log (truncated exponential(152,1,400))

SE_{ij} = Log_{10} S. Enteritidis at end of a step = $SE_{i(j-1)} + (ERG_{ij} * tG_{ij})$

If $SE_{ij} > 10.0$, then set $Se_{ij} = 10.0$

Growth of SE stops at log_{10} 10.0

Note: °F to °C and hour to day conversions are not detailed

H. References

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