AN INVENTORY MODEL FOR MECHANICAL SEALS AT THAI LUBE BASE REFINERY

by

Mr. Pisit Fusiripong

A Final Report of the Three - Credit Course
CE 6998 Project

Submitted in Partial Fulfillment
of the Requirements for the Degree of
Master of Science
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Project Title	An Inventory Model for Mechanical Seals at Thai Lube Base Refinery
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The Graduate School of Assumption University has approved this final report of the three-credit course, CE 6998 PROJECT, submitted in partial fulfillment of the requirements for the degree of Master of Science in Computer and Engineering Management.

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ABSTRACT

This project examines the preparation of an inventory model for mechanical seal in Thai Lube Base Refinery.

Thai Lube Base (Public) CO., LTD (THAILUBE) was founded in 1995. The business is refinery. This refinery was started in 1997. There are many equipment in this company. The equipment were distinguished in two categories: 1. Statutory Equipment: heat exchanger, furnace, etc. 2. Rotating Equipment: pump, compressor, etc.

During operating period, THAILUBE frequently encountered the mechanical seal failure problem. In this refinery, there are approximately 300 mechanical seals. But only some mechanical seals were failure, others were in good condition – no failure found. Therefore, this refinery must stock component parts of mechanical seal in the warehouse.

Since 1997, it has been found that some parts of mechanical seal were frequently used, but some parts were rarely used. Due to economic crisis, management level planned to reduce the inventory cost. Therefore, it was recommended to develop the inventory model of mechanical seals that maximize the productivity of the refinery.

The inventory model for mechanical seal was developed. The steps of developing the inventory model for mechanical seal are:

(1) To do the criticality assessment of equipment.

(2) To review the MTBF (mean time between failure of each equipment).

(3) To review the component parts of mechanical seal

(4) To develop inventory model according to criticality and MTBF.

After the inventory model was developed, the inventory cost of this refinery was reduced but the productivity of this refinery is still good.

ACKNOWLEDGEMENTS

I am indebted to the following people and organizations. Without them, this project would not have been possible.

I wish to express my sincere gratitude to my advisor, Dr. Aran Namphol. His patient assistance, guidance, and constant encouragement has led me from the reseach inception to research completion.

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I. INTRODUCTION

Recently, Thai Lube Base Refinery focuses on the development of the inventory model for whole spare parts in the warehouse. The inventory cost of this refinery is around 5 million US$. Thai Lube Base Refinery would like to reduce the inventory cost, but the productivity is still good.

1.1 Background of Refinery

The Thai Lube Base Refinery is sited on over 130 rai of land on Ao Udom Road, Amphur Sriracha, Chonburi Province. The construction commenced in August 1994. According to the operation plan, the refinery started in 1997.

The investment has been supported from its shareholders (please see percentage of shareholders at Figure 1.1). Commencing at only bht 350 million, now the registered capital of Thailube has reached bht 4,600 million. Earning investment and financial reliability, the company gained long-term loan of US$ 195 million from domestic and international financial institutions for project implementation.

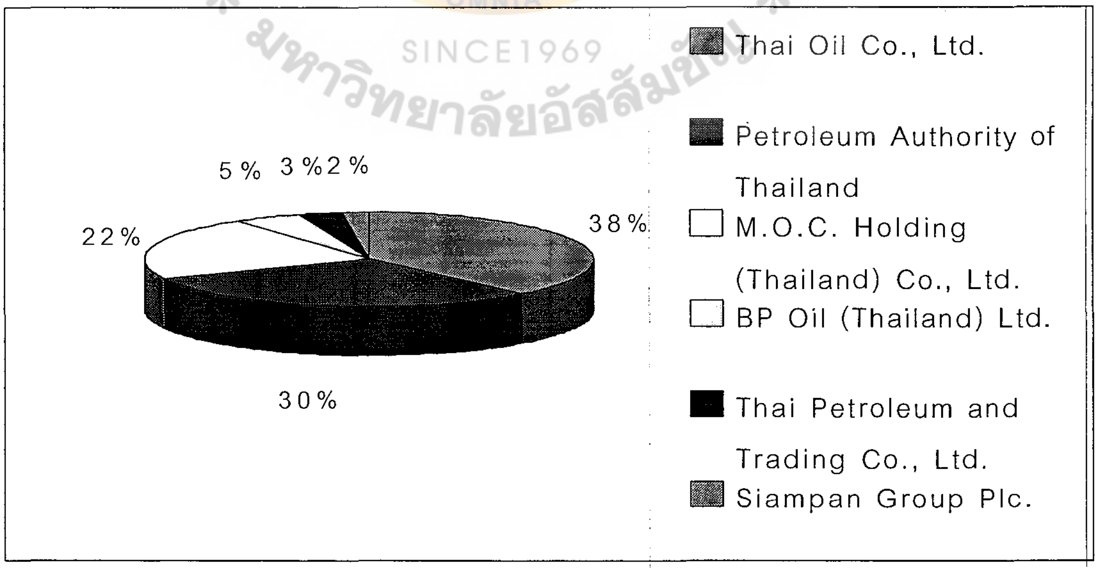

Figure 1.1. Percentage of Shareholders.

The company intends to sell its products mainly to the domestic market. Consequently, lube base oil purchase and sales agreements were signed with the shareholders, mostly the country's major lubricant producers and distributors. A long-term agreement of the sales of bitumen was also signed with a domestic asphalt trader.

The initial feed stock is long residue imported from the Middle East and other replaceable sources. A long-term purchase contract was signed with a Saudi Arabian producer. The shareholders' support will also ensure the security of feed stock supply for the Refinery operation.

In the production, the Company employs advanced technology of Texaco Development Corporation from the United States, a company wildly recognized in the lubricant industry for its superior technology. This will guarantee that the production be strictly controlled throughout the process to attain world standard quality.

The main processes of this refinery are composed of:

(1) VDU (Vacuum Distillation Unit): Long residue is fed from storage to a VDU, designed to produce three waxy distillate cuts suitable for processing into finished lube base oils and also vacuum residue.

(2) PDA (Propane Deasphalting Unit): The vacuum residue from the VDU is fed to a PDA to produce a deasphalted oil suitable for manufacturing of 150 Bright Stock lube base oil.

(3) MPU (MP Refining Unit): The three waxy distillates and deasphalted oil are solvent extracted by NMP or n-Methyl-2-Pyrrolidone to selectively removed undesired aromatic compound which has poor lubricating characteristics and poor oxidation stability. The process improves the viscosity index of the oil.

(4) HFU (Hydrogen Finishing Unit): The product from the MPU is fed directly to the HFU, where it is treated with hydrogen in the presence of a catalyst. This removes sulphur compounds from the base oil, to achieve product specifications and improve the color and oxidation stability.

(5) SDU (Solvent Dewaxing Unit): The treated oil from HFU is fed directly to the SDU, which removed naturally-occurring waxes from the base oil by precipitating out wax in crystalline form. The unit operates at a low temperature in order to produce base oil with a low pour point.

By the end of the process, four grades of lube base oil prevail:

(a) 60SNO: This product is used as raw material for producing transmission fluid, transformer oil, and refrigerating oil.

(b) 150SNO: This product is raw material in producing industrial lube oils used in automobile and transportation industry.

(c) 500SNO: This product is used as raw material for lubricants for nearly all types of automobiles.

(d) 150BS: This product is used to lubricate high grazing engines such as high/low speed diesel engines of trucks, trains and marine ships.

The Refinery's output are usually blended with various additives according to the required formula, to produce finished lubricants to be used in automotive and transport industries, marine and aviation sectors, and other manufacturing industries.

The Refinery also yields a variety of by-products. Among the most significant is bitumen, used as raw materials in producing asphalt for road surface repair, construction of asphalted roads, and joining of concrete road seam. Others include sulphur, slack wax, naphtha etc., which are feed stock for downstream industries like tires, paint, detergent, car batteries, cosmetics, casing and so on.

The Refinery will produce some 300 million liters of paraffinic lube base oil, 350 million liters of bitumen, and 600 million liters of other by-products annually, representing 24%, 28%, and 48% of the total yield respectively.

1.2 Financial Problem

Last two years, our country encountered the financial problem. Many companies would be closed, re-organized the structure and so on. Also Thailube encountered this situation. But, Thailube is still operated.

However, Thailube must reduce the cost in the company to cope the financial situation. There are many ways to solve this situation.

To reduce the inventory of spare part is the one solution of cost reduction. However, we must stock the important parts for eliminating the production problem.

1.3 Research Objectives

In the refinery, there are many types of equipment for refining such as heat exchanger, column, tank, pump, and etc. The main problem in the refinery as encounter is the failure of mechanical seal. The mechanical seal is one component of pump.

In this refinery, there are around 300 mechanical seals. When the mechanical seals were repaired, some parts should be replaced, Therefore, this refinery must stock parts in the warehouse for maintenance work. If the mechanical seals cannot be fixed in time, it may cause the refinery to shut down; that means loss of productivity.

However, some pumps do not effected the productivity of the refinery. These pumps can be waiting for a long time before putting them on service. But, some pumps are very important for the refinery. These pumps must be repaired in time because they will cause delay to the productivity.

In this research, we will focus only on the mechanical seal because this part is also important for equipment and mean time between failure of mechanical seal is so high.

So, the refinery still stocks important mechanical seals in the warehouse for protecting the productivity of plant.

The objective for this research is to develop an inventory model of mechanical seal that maximize the productivity of the refinery.

1.4 Scope of Research

The scope of this research is to analyze the rotating equipment, which is the critical equipment, and to make the minimum stock of mechanical seal.

1.5 Benefit of Research

The benefit of this research can be distinguished as following:

(1) The effective inventory model for mechanical seal will be got. The cost of inventory will be reduced.

(2) Information about parts such as MTBF, design data will be collected.

1.6 Project Plan

Table 1.1. Project Plan.

Item	Description	Duration	Date
1	Study criticality assessment theory and list equipment	10 days	01/04/00-10/04/00
2	Set criteria of critical assessment	21 days	11/04/00-01/05/00
3	Analyze criticality of equipment	60 days	02/05/00-30/06/00
4	Study inventory model and check number of parts	10 days	01/07/00-10/07/00
5	Make inventory model	20 days	11/07/00-31/07/00
6	Make minimum stock of each equipment	60 days	01/08/00-30/09/00
7	Submit the project	1 day	14/10/00
8	Approve the project	5 days	15/10/00-20/10/00
9	Presentation	1 day	18/11/00

II. LITERATURE REVIEW

In this chapter, the readers will know the detail of mechanical seal and the method of criticality assessment.

2.1 Mechanical Seals

2.1.1 Principle of Operation

Mechanical seal is one component of rotating equipment especially pump. The function of it is to prevent the leakage between rotating shaft of rotating equipment and their housing.

The old method of preventing the leakage is using soft packing. The old method had many disadvantages, for example, the packing must be regularly inspected and tightened down to take up wear, and it must also be replaced frequently. In time, the pump shaft or sleeve becomes worn, necessitating expensive renovation. Since the packed gland relies for its successful operation on lubrication of packing material by the fluid being pumped, it can never entirely stop leakage, unless a costly liquid sealing system is introduced.

Mechanical seals overcome these advantages. There is a wide range of seals available, differing in design and application, but all applying certain basic design considerations.

The principle components of the mechanical seal were composed of 1. Stationary seal ring 2. Stationary seal ring packing 3. Rotary seal ring 4. Rotary seal ring packing 5. Spring.

Sealing action is obtained by intimate contact between the opposing faces of two rings, one of which is held resiliently (stationary seal ring) in the gland housing while the other (rotary seal ring) rotates with the shaft. As the rubbing surfaces are extremely flat – they are lapped within two light bands – leakage of the fluid being handled is prevented.

2.1.2 Stationary Seal Rings

The stationary seal ring, usually made from a specially compounded grade of carbon, is resiliently mounted on stationary seal ring packing. The stationary seal ring is provided with a slot to enable the ring to be positively located in the seal housing, thus preventing its rotation.

2.1.3 Stationary Seal Ring Packings

The stationary seal ring packing prevents leakage between the stationary seal ring and the gland housing.

2.1.4 Rotary Seal Rings

The rotary seal ring rotates with, and is driven by, the shaft. In mechanical seals, the rotary seal ring is normally the hard face.

2.1.5 Rotary Seal Ring Packings

The rotary seal ring packing effectively prevents leakage between the rotary seal ring and the shaft, while allowing the ring sufficient freedom of movement to maintain full face contact with the stationary seal ring.

2.1.6 Spring Drives

Initial seal face contact is maintained by spring. Interference fit between the spring and the shaft at one end and the neck of the rotary seal ring at the other provides a positive resilient drive.

2.2 The Criticality Assessment

2.2.1 What Is The Criticality Assessment?

There are many pumps in this plant. Some pumps are so significant, but some pumps are not so important for operation of this plant. The mechanical seal is the component of the pump. If the mechanical seal has failure, it can cause a loss of productivity of this plant.

Generally, the mechanical seal can fail all the time. The failure of mechanical seal depends on operation, design, model and etc. Some mechanical seals will have low probability of failure, but some mechanical seals have extreme probability of failure.

The criticality assessment is the method that assessed the equipment by using two parameters for assessment - probability of failure and consequences of failure. After the equipment has already been assessed, it would find the equipment which one is so important or negligible.

2.2.2 How to Do The Criticality Assessment?

Criticality (risk of failure) is defined as the combination of two parameters, probability of failure and consequence of failure, and is presented in the form of matrix. A 3*3 criticality matrix is used.

The probability of failure is assessed using "questionnaires", which use relevant information regarding process conditions and degradation mechanisms for the system concerned. The "questionnaires" for consequences of failure takes account of consequences in the areas of safety, environment, economics and operations.

Both the probability of failure and consequences of failure are sub-divided into 3 categories composed of "Low", "Medium" and "High". The criticality matrix (please see criticality matrix at Figure 2.1), in which the Criticality Rating is determined by combining the two parameters - probability of failure and consequences of failures, comprises 5 levels composed of Extreme, High, Medium, Low, and Negligible.

Probability of Failure

High	**M**	**H**	**E**
Medium	**L**	**M**	**H**
Low	**N**	**L**	**M**
	Low	**Medium**	**High**

Consequences of Failure

Where

E	Extreme
H	High
M	Medium
L	Low
N	Negligible

Figure 2.1. Criticality Matrix.

2.2.3 How to Get the Consequence of Failure?

Consequence of Failure is the result of failure in the areas of safety, production, environment, and commercials. If the result of failure is so high, this equipment must be extremely critical because it may effect the plant in terms of safety, production, environment or commercial so much.

The consequence of failures questionnaire will use 4 criteria to determine consequences rating as follows:

(1) Production Impact (A1)

(2) Safety Impact (A2)

(3) Environmental Impact(A3)

(4) Commercial Impact(Cost) (A4)

The overall consequence rating is based on: either the arithmetical average of Production Impact, Safety Impact and Environment Impact or the commercial impact (Cost) whichever is the lower of the two, i.e. higher consequence rating.

The calculation will be:

min((A1+A2+A3)/3 or A4)

The criteria for each impact will be described as the following:

(a) Production Impact (A1) will be scored as per the following condition:

Table 2.1. Production Impact Questionnaires.

Failure would cause to	Rank
- result of failure will make major plant shut down	1
- result in moderate effect such as shutdown only unit, quality of product off-spec in few period time	2
- the equipment failure without effect on production, allow use of bypass or have redundancy equipment	3

(b) Safety Impact (A2) will be scored as per the following condition:

Table 2.2. Safety Impact Questionnaires.

Failure would cause to	Rank
- effect safety equipment or protection equipment	1
- result directly endanger to man and plant	2
- result in negligible safety condition	3

(c) Environmental Impact (A3) will be scored as per the following condition:

Table 2.3. Environmental Impact Questionnaires.

Failure would cause to	Rank
- environmental pollution e.g. a release of pollutants to water at compliant level or release to the atmosphere in excess of the short term exposure limit	1
- environment nuisance i.e. odors, visible cloud, heavy flare etc. or a release to the atmosphere in excess of the long term exposure limit or release of liquids within the capacity of site containment	2
- no environment hazard i.e. release of clean water, inert gas etc.	3

(d) Commercial Impact (Cost) (A4) will be scored as per the following condition:

Cost = Production Cost + Opportunity Loss Cost + Maintenance Cost

Table 2.4. Commercial Impact Questionnaires.

Failure would cause to	Rank
- result in high opportunity loss cost (greater than 1,000,000 bahts)	1
- result in moderate opportunity loss cost (greater than 500,000 bahts but less then 1,000,000 bahts)	2
- result in negligible opportunity loss cost (less than 500,000 bahts)	3

The Consequence assessment should be carried out by team ensuring input by all expertise areas to enable them to make sound judgments on safety, environmental, production and commercial impacts.

On completion of the Consequences Questionnaires and calculating them, the consequence of failure rating will be got. Then we will know the consequence level as per following table.

Table 2.5. Consequence Level.

Overall Consequence Rating	Consequence Level
Up to and including 1.5	High
From 1.5 up to and including 2	Medium
From 2 up to and equal to 3	Low

2.2.4 How to Get The Probability of Failure?

The probability of failure is the chance of failure of equipment to be occurred by using relevant information regarding process conditions and degradation mechanisms for the system concerned.

The probability of failure rating is based on the evaluation of appropriate failure modes for the type of equipment being assessed as described in the following sections.

Each failure mode is evaluated on a basis of high, medium or low probability according to a model or a set of rules.

The overall rating is the highest failure probability.

Table 2.6. Probability Level.

Score	Probability Level
1	High
2	Medium
3	Low

<u>Failure Modes – Piping and Static Equipment</u>

(1) Internal Corrosion – Predicted Remaining Life: (Calculated from plant age, corrosion allowance and predicted corrosion rate)

(a) Rating 3 (low) ....greater than 10 years

(b) Rating 2 (medium)........greater than 5 years and less than 10 years

(c) Rating 1 (high)...........less than 5 years

Remaining Life Calculation:

(a) Age of plant or equipment is known.

(b) For piping run ANSI B31.3 thickness calculation

(c) Subtract minimum thickness from nominal wall to determine maximum allowance loss.

(d) Determine rate from: Plant monitoring data, Specific models, Corrosion rate.

(e) Calculate time to consume allowable loss.

(2) External Corrosion – Predicted Remaining Life: (Calculated from plant age, corrosion allowance and predicted corrosion rate)

(a) Rating 3 (low) .... greater than 10 years

(b) Rating 2 (medium).....greater than 5 years and less than 10 years

(c) Rating 1 (high)..........less than 5 years

(3) Erosion – Calculated Velocity: (Lines in two phase service with)

(a) Rating 3 (low) .... less than API RP14E erosional velocity

(b) Rating 2 (medium)......greater than API RP14E erosional velocity and less than Conoco modification of RP14E

(c) Rating 1 (high)......... greater than Conoco modification of RP14E

(4) Cavitation: (Lines in liquid or two phase service containing control valve with)

(a) Rating 3 (low) .... less than 5 bar pressure drop

(b) Rating 2 (medium)...... greater than 5 bar and less than 10 bar pressure drop

(c) Rating 1 (high)......... greater than 10 bar pressure drop

(5) Creep: (Applied to plants older than 15 years with)

(a) Rating 3 (low) .... design and operating temperatures less than ASME limits

(b) Rating 2 (medium)...... design or upset temperatures greater than ASME limits

(c) Rating 1 (high)......... operating temperatures greater than ASME limits

(6) Fatigue - Vibration: (Lines or equipment directly connected to reciprocating equipment with)

(a) Rating 3 (low) .... nominal diameter greater than 4 inch or no nozzles less than 4 inch

(b) Rating 2 (medium)...... nominal diameter or smallest nozzle 2 to 4 inch

(c) Rating 1 (high)......... nominal diameter or smallest nozzle less than 2 inch

(7) Fatigue - Thermal: (Lines or equipment in thermal cyclic service with)

(a) Rating 3 (low) .... all other lines and equipment

(b) Rating 2 (medium)...... cyclic temperature range 200 to 300 degree C

(c) Rating 1 (high)......... cyclic temperature range greater than 300 degree C

(8) Stress Corrosion Cracking – Material is:

(a) Rating 3 (low) .... not susceptible under any foreseen conditions

(b) Rating 2 (medium)...... susceptible under design or upset conditions

(c) Rating 1 (high)......... susceptible under operating conditions

(9) Low Temperature Embrittlement:

(a) Rating 3 (low) .... design, upset and operating temperatures greater than ASME limits

(b) Rating 2 (medium)...... design or upset temperatures less than ASME limits

(c) Rating 1 (high)......... operating temperature less than ASME limits

(10) High Temperature Embrittlement:

(a) Rating 3 (low) .... design, upset and operating temperatures less than ASME limits

(b) Rating 2 (medium)...... design or upset temperatures greater than ASME limits

(c) Rating 1 (high)……… operating temperature greater than ASME limits

(11) Wet Hydrogen Cracking – Material is:

(a) Rating 3 (low) ……… resistant in the as-welded condition or no environmental source of atomic hydrogen (H2S, HCN, HF etc.)

(b) Rating 2 (medium) …… requires hardness control or post weld heat treatment for resistance. Hardness control or PWHT specified

(c) Rating 1 (high)……… requires hardness control or post weld heat treatment for resistance. Hardness control or PWHT not specified

(12) Hot Hydrogen Attack – Material is:

(a) Rating 3 (low) ……… not susceptible under any foreseen conditions

(b) Rating 2 (medium)…… susceptible under design or upset conditions

(c) Rating 1 (high)……… susceptible under operating conditions

(13) Process Fouling: (Based on plant operating data)

(a) Rating 3 (low) ……… non fouling service

(b) Rating 2 (medium)…… fouling under upset conditions

(c) Rating 1 (high)……… fouling under normal operating conditions

<u>Failure Modes – Rotating Equipment</u>

(1) Seal Failure (seal failure probability begins at low, medium, or high depending on type. Rating is modified according to several factors until a final rating is reached)

(a) Initial probability ratings

(1) Rating 3 (low) ……… single seals and glandless equipment

(2) Rating 2 (medium)…… double and tandem seals

(3) Rating 1 (high)……… packed glands

Operating Temperature:

(a) Rating +1 (lower) ……… 10 to 50 degree C

(b) Rating 0 (no change)…… less than 10 degree C or between 50 and 250 degree C (100 degree C for tandem seals)

(c) Rating -1 (higher)……… greater than 250 degree C (100 degree C for tandem seals)

Operating Point:

(a) Rating +1 (lower) ……… normally operates at 60 to 110% of flow at BEP

(b) Rating 0 (no change)…… normally operates at 30 to 60% or greater than 110% of flow at BEP

(c) Rating -1 (higher)……… normally operates at less than 30% of flow at BEP

Product Vapor Pressure:

(a) Rating 0 (no change)…… vapor pressure less than suction pressure

(b) Rating -1 (higher)……… vapor pressure greater than suction pressure

Fluid Solids Content:

(a) Rating 0 (no change)…… clean product

(b) Rating -1 (higher)……… product contains solids under normal or upset conditions

(b) Seal Failure MTBF (actual Mean Time Between Failures data for seals may be used to overwrite the ratings generated from the previous operational factors)

(1) Rating 3 (low) ……… MTBF greater than 3 years

(2) Rating 2 (medium)…… MTBF greater than 1 year and less than 3 years

(3) Rating 1 (high)……… MTBF less than 1 year

(2) Bearing Failure (bearing failure probability begins at low, medium, or high depending on type. Rating is modified according to several factors until a final rating is reached)

(a) Initial probability ratings

(1) Rating 3 (low) ……… lubricated by oil mist or independent lubricating oil system

(2) Rating 2 (medium)…… lubricated by oil bath system

(3) Rating 1 (high)……… lubricated by grease or product

Speed:

(a) Rating 0 (no change)…… running speed less than 3000 RPM

(b) Rating -1 (higher)……… running speed 3000 RPM and greater

Operating Temperature:

(a) Rating +1 (lower) ……… 10 to 50 degree C

(b) Rating 0 (no change)…… less than 10 degree C or between 50 and 250 degree C

(c) Rating -1 (higher)……… greater than 250 degree C

Operating Mode:

(a) Rating +1 (lower) .... continuous operation, unspared

(b) Rating 0 (no change)...... continuous operation, spared

(c) Rating -1 (higher)......... intermittent, batch or occasional duty

Suction protection:

(a) Rating 0 (no change)...... minimum flow or suction protection installed

(b) Rating -1 (higher)......... minimum flow or suction protection not installed

(b) Bearing Failure MTBF (actual Mean Time Between Failures data for bearings may be used to overwrite the ratings generated from the previous operational factors)

(1) Rating 3 (low) .... MTBF greater than 3 years

(2) Rating 2 (medium)...... MTBF greater than 1 year and less than 3 years

(3) Rating 1 (high)......... MTBF less than 1 year

(3) Coupling Failure:

(a) Rating 3 (low) .... product viscosity less than 10 Cst or product viscosity between 10 and 100 Cst and continuous duty or product viscosity greater than 100 Cst at ambient temperature and continuous duty, unspared

(b) Rating 2 (medium)...... product viscosity between 10 and 100 Cst and intermittent or batch duty or product viscosity greater than 100 Cst at ambient temperature and continuous duty, spared

(c) Rating 1 (high)......... product viscosity greater than 100 Cst at ambient temperature and intermittent or batch duty

(4) Driver Failure:

(a) Rating 3 (low) .... electric motor or turbine with power greater than 150 kW

(b) Rating 2 (medium)...... internal combustion engine or turbine with power less than 150 kW

(c) Rating 1 (high)......... reciprocating steam engine

(5) Internal Failure:

(a) Rating 3 (low) .... internal components resistant to corrosion in process fluid and product vapor pressure less than suction pressure and solids not present in fluid

(b) Rating 2 (medium)...... galvanic attack of internal components possible or product vapor pressure greater than suction pressure

(c) Rating 1 (high)......... internal components not resistant to corrosion in process fluid or solids present in fluid

(6) Pressure Envelope Failure:

(a) Rating 3 (low) .... casing resistant to corrosion in process fluid

(b) Rating 2 (medium)...... galvanic attack of casing by internal component possible

(c) Rating 1 (high)......... casing not resistant to corrosion in process fluid

III. INVENTORY MODELS

An industry usually maintains a reasonable inventory of goods to ensure smooth operation. Traditionally, inventory is viewed as a necessary evil – too little of it causes costly interruptions, too much results in idle capital. The inventory problem determines the inventory level that balances the two extreme cases.

An important factor in the formulation and solution of an inventory model is that the demand (per unit time) of an item may be deterministic or probabilistic.

3.1 A Deterministic Inventory Model

3.1.1 A General Inventory Model

The nature of the inventory problem consists of repeatedly placing and receiving orders of given sizes at set intervals. From this standpoint, an inventory policy answers the following two questions:

(1) How much to order?

(2) When to order?

The answer to the first question determines the economic order quantity (EOQ) by minimizing the following cost model:

(Total Inventory Cost) = (Purchasing Cost) + (Setup Cost) + (Holding Cost) + (Shortage Cost)

All these costs must be expressed in terms of desired order quantity and the time between orders:

(1) Purchasing cost is based on the price per unit of the item. It may be constant, or it may be offered at a discount that depends on the size of the order.

(2) Setup cost represents the fixed charge incurred when an order is placed. This cost is independent of the size of the order.

(3) Holding cost represents the cost of maintaining the inventory in stock. It includes the interest on capital as well as the cost of storage, maintenance, and handling.

(4) Shortage cost is the penalty incurred when we run out of stock. It includes potential loss of income as well as the more subjective cost of loss in customer's goodwill.

The answer to the second question (when to order?) depends on the type of inventory system with which we are dealing. If the system requires periodic review (e.g., every week or month), the time for receiving a new order coincides with the start of each period. Alternatively, if the system is based on continuous review, new orders are placed when the inventory level drops to a pre-specified level, called the reorder point.

3.1.2 A Classic EOQ Model

The simplest of the inventory models involves constant rate demand with instantaneous order replenishment and no shortage. Let:

y = Order quantity (number of units)

D = Demand rate (units per unit time)

t_0 = Ordering cycle length (time units)

An order of size y units is placed and received instantaneously when the inventory level is zero. The stock is then depleted uniformly at the constant demand rate D. The ordering cycle for this pattern is:

t_0 = y/D time units

The resulting average inventory level is given as:

Average inventory level = y/2 unit

The cost model requires two cost parameters.

K = Setup cost associated with the placement of an order (cost per order)

h = Holding cost (cost per inventory unit per unit time)

The total cost per unit (TCU) is thus computed as:

TCU(y) = Setup cost per unit time + Holding cost per unit time

= Setup cost + Holding cost per cycle t_0 / t_0

= K + h(y/2) t_0) / t_0

The optimum value of the order quantity y is determined by minimizing TCU(y) with respect to y. Assuming y is continuous, a necessary condition for finding the optimal value of y is:

$$d\text{TCU}(y)/dy = -KD/y^2 + h/2 = 0$$

The condition is also sufficient because TCU(y) is convex. The solution of the equation yields the EOQ y* as:

y* = Sqrt (2KD/h)

The optimum inventory policy for the proposed model is summarized as:

Order y* = Sqrt (2KD/h) units every t_0^* = y*/D time units

Actually, a new order need not be received at the instant it is ordered as the preceding discussion suggests. Instead, a positive lead-time, L, may occur between the placement and the receipt of an order. In this case, the reorder point occurs when the inventory level drops to LD units.

3.2 A Probabilistic Inventory Model

This section presents two models: (1) a "propabilitized" version of the deterministic EOQ (Section 3.1) that uses a buffer stock to account for probabilistic demand, and (2) a more exact probabilistic EOQ model that includes the probabilistic demand directly in the formulation.

3.2.1 A "Probabilitized" EOQ Model

Some practitioners have sought to adapt the deterministic EOQ model (Section 3.1) to reflect the probabilistic nature of demand by using an approximation that superimposes a constant buffer stock on the inventory level throughout the entire planning horizon. The size of the buffer is determined such that the probability of running out of stock during lead time (the period between placing and receiving an order) does not exceed a pre-specified value.

Let:

L	=	Lead time between placing and receiving an order
X_L	=	Random variable representing demand during lead time
μ_L	=	Average demand during lead time
σ_L	=	Standard deviation of demand during lead time
B	=	Buffer stock size
α	=	Maximum allowable probability of running out of stock during lead time

The main assumption of the model is that the demand, XL, during lead time L is normally distributed with mean L and standard deviation L – that is, N (μ_L,σ_L)

The demand during the lead time, L, usually is descibed by a probability density function per unit time (e.g., per day or week), from which we can determine the distribution of the demand during L. Specifically, given that the demand per unit time is normal with mean D and standard devistion , then, in general, the demand during L is N (μ_L, L), where:

$$\mu_L = DL$$

$$\sigma_L = sqrt\ (\sigma^2 L)$$

The formula for σ_L requires L to be (rounded to) an integer value.

3.2.2 A Probabilistic EOQ Model

There is no reason to believe that the "probabilitized" EOQ model will produce an optimal inventory policy. The fact that pertinent information regarding the probabilistic nature of demand is initially ignored, only to be "received" in a totally independent manner at a later stage of the calculations, is sufficient to refute optimality. To remedy the situation, a more accurate model is presented in which the probabilistic nature of the demand is included directly in the formulation of the model.

Unlike the case in Probabilitized EOQ model, the new model allows shortage of demand. The policy calls for ordering the quantity y whenever the inventory drops to level R. As in the deterministic case, the reorder level R is a function of the lead time between placing and receiving an order. The optimal values of y and R are determined by minimizing the expected cost per unit time that includes the sum of the setup, holding, and shortage costs.

The model has three assumptions:

(1) Unfilled demand during lead time is backlogged.

(2) No more than one outstanding order is allowed.

(3) The distribution of demand during lead time remains stationary (unchanged) with time.

To develop the total cost function per unit time, let:

$f(x)$ = pdf of demand, x, during lead time

D = Expected demand per unit time

h = Holding cost per inventory unit per unit time

p = Shortage cost per inventory unit

K = Setup cost per order

Based on these definitions, the elements of the cost function are now determined.

(1) Setup cost. The approximate number of order of orders per unit time is *D/y*, so that the setup cost per unit time is *KD/y*.

(2) Expected holding cost. The average inventory is:

$$I = \frac{(y + E\{R - x\}) + E\{R - x\}}{2} = \frac{y}{2} + R - E\{x\}$$

The expected holding cost per unit time thus equals *hI*.

The formula is based on the average of the beginning and ending expected inventories of a cycle, y + E {R – x } and E{R – x }, respectively. As an approximation, the expression ignores the case where R - E{x} may be negative.

(3) Expected shortage cost. Shortage occurs when x > R. Thus, the expected shortage quantity per cycle is:

$$S = \int_R^{\infty} (x - R)\, f(x)dx$$

Because *p* is assumed to be proportional to the shortage quantity only, the expected shortage cost per cycle is *pS*, and, based on *D/y* cycles per unit time, the shortage cost per unit time is *pDS/y*.

The resulting total cost function per unit time is:

$$TCU(y, R) = DK/y + h(y/2 + R - E\{x\}) + pD/y\int_R^{\infty} (x - R)f(x)dx$$

The solutions for optimal y^* and R^* are determined from:

$$\partial TCU/\partial y = -(DK/y^2) + h/2 - pDS/y^2 = 0$$

$$\partial TCU/\partial R = h - (pD/y)\int_R^{\infty} f(x)dx = 0$$

We thus get:

$$y^* = \text{sqrt}\,(2D(K + pS)/h) \qquad (1)$$

$$\int_R^{\infty} f(x)dx = hy^*/pD \qquad (2)$$

Because y^* and R^* cannot be determined in closed forms from (1) and (2), a numeric algorithm, developed by Hadley and Whitin, is used to find the solutions. The algorithm is proved to converge in a finite number of iterations, provided a feasible solution exists.

For R = 0, the last two equations, respectively, yield:

$y^\wedge$ = sqrt (2D(K + pE{x})/h

$y^\sim$ = pD/h

If $y^\sim \geq y^\wedge$, unique optimal values of y and R exist. The solution procedure recognizes that the smallest value of y^* is sqrt (2KD/h), which is achieved when S = 0.

The steps of the algorithm are:

Step 0: Use the initial solution $y_1 = y^*$ = sqrt (2KD/h), and let $R_0 = 0$. Set i = 1, and go to step i.

Step i: Use y_i to determine R_i from Equation (2). If $R_i \approx R_{i-1}$, stop; the optimal solution is $y^* = y_i$, and $R^* = R_i$. Otherwise, use R_i in Equation (1) to compute y_i. Set i = i + 1, and repeat step i.

IV. AN INVENTORY MODEL FOR MECHANICAL SEALS AT THAI LUBE BASE REFINERY

4.1 An Introduction

There are 268 pumps in Thailube. The cost of mechanical seal inventory for these pumps is around 36,000,000 bahts. This cost is very so high. Moreover, the MTBF of all mechanical seals is around 4 years.

Due to economic crisis, management planned to reduce the cost. Therefore, the inventory cost is one of the costs that management would like to reduce. But it is still insisted that the productivity of product must not be interrupted.

The mechanical seals are the major parts that were broken down during running for 3 years. After the mechanical seals were broken down, they must be replaced by the new one. The average cost of mechanical seal each is around 150,000 bahts.

In this report, the inventory cost of mechanical seal was focused to reduce them down, but the productivity is still being good.

4.2 The Criticality Assessment of Pumps

4.2.1 The Consequence of Failure of Pumps

As per the questionnaires of consequence of failure of pumps, the consequence of failure for each pump can be listed as the following table:

Table 4.1. Consequences Assessment of Pumps in Thailube.

Item	Tag	A1	A2	A3	A4	Consequence Rating	Consequence Level
1	100L-P-101A	2	3	3	3	3	L
2	100L-P-101B	2	3	3	3	3	L
3	100L-P-102A	3	3	3	3	3	L
4	100L-P-102B	3	3	3	3	3	L

Table 4.1. Consequences Assessment of Pumps in Thailube. (Continued)

Item	Tag	A1	A2	A3	A4	Consequence Rating	Consequence Level
5	100L-P-103A	3	3	3	3	3	L
6	100L-P-103B	3	3	3	3	3	L
7	100L-P-104A	3	3	3	3	3	L
8	100L-P-104B	3	3	3	3	3	L
9	100L-P-105A	3	3	3	3	3	L
10	100L-P-105B	3	3	3	3	3	L
11	100L-P-106A	3	3	3	3	3	L
12	100L-P-106B	3	3	3	3	3	L
13	100L-P-107A	3	3	3	3	3	L
14	100L-P-107B	3	3	3	3	3	L
15	100L-P-108A	3	3	3	3	3	L
16	100L-P-108B	3	3	3	3	3	L
17	100L-P-109A	3	3	3	3	3	L
18	100L-P-109B	3	3	3	3	3	L
19	100L-P-110A	3	3	3	3	3	L
20	100L-P-110B	3	3	3	3	3	L
21	100L-P-111A	3	3	3	3	3	L
22	100L-P-111B	3	3	3	3	3	L
23	100L-P-112A	3	3	3	3	3	L
24	100L-P-112B	3	3	3	3	3	L
25	100L-P-113A	3	3	3	3	3	L
26	100L-P-113B	3	3	3	3	3	L
27	100L-P-121A	3	3	3	3	3	L
28	100L-P-121B	3	3	3	3	3	L
29	200L-P-101A	2	3	3	3	2.7	L
30	200L-P-101B	2	3	3	3	2.7	L
31	200L-P-102A	3	3	3	3	3	L
32	200L-P-102B	3	3	3	3	3	L

Table 4.1. Consequences Assessment of Pumps in Thailube. (Continued)

Item	Tag	A1	A2	A3	A4	Consequence Rating	Consequence Level
33	200L-P-103A	2	3	3	3	2.7	L
34	200L-P-103B	2	3	3	3	2.7	L
35	200L-P-104A	2	3	3	3	2.7	L
36	200L-P-104B	2	3	3	3	2.7	L
37	200L-P-105A	3	3	3	3	3	L
38	200L-P-105B	3	3	3	3	3	L
39	200L-P-106A	3	3	3	3	3	L
40	200L-P-106B	3	3	3	3	3	L
41	200L-P-107A	3	3	3	3	3	L
42	200L-P-107B	3	3	3	3	3	L
43	200L-P-108	3	3	2	3	2.7	L
44	300L-P-101A	3	3	3	3	3	L
45	300L-P-101B	3	3	3	3	3	L
46	300L-P-102A	3	3	3	3	3	L
47	300L-P-102B	3	3	3	3	3	L
48	300L-P-103A	3	3	3	3	3	L
49	300L-P-103B	3	3	3	3	3	L
50	300L-P-104A	3	3	3	3	3	L
51	300L-P-104B	3	3	3	3	3	L
52	300L-P-105A	3	3	3	3	3	L
53	300L-P-105B	3	3	3	3	3	L
54	300L-P-106A	3	3	3	3	3	L
55	300L-P-106B	3	3	3	3	3	L
56	300L-P-107A	3	3	3	3	3	L
57	300L-P-107B	3	3	3	3	3	L
58	300L-P-108A	3	3	3	3	3	L
59	300L-P-108B	3	3	3	3	3	L
60	300L-P-109A	3	3	3	3	3	L

Table 4.1. Consequences Assessment of Pumps in Thailube. (Continued)

Item	Tag	A1	A2	A3	A4	Consequence Rating	Consequence Level
61	300L-P-109B	3	3	3	3	3	L
62	300L-P-110A	2	3	3	3	2.7	L
63	300L-P-110B	2	3	3	3	2.7	L
64	300L-P-111A	3	3	3	3	3	L
65	300L-P-111B	3	3	3	3	3	L
66	300L-P-112	3	3	3	3	3	L
67	300L-P-113	3	3	3	3	3	L
68	300L-P-114A	3	3	3	3	3	L
69	300L-P-114B	3	3	3	3	3	L
70	300L-P-115	3	3	3	3	3	L
71	300L-P-116A	3	3	3	3	3	L
72	300L-P-116B	3	3	3	3	3	L
73	300L-P-117	2	3	3	1	1	H
74	300L-P-151A	3	3	3	3	3	L
75	300L-P-151B	3	3	3	3	3	L
76	400L-P-101A	3	3	3	3	3	L
77	400L-P-101B	3	3	3	3	3	L
78	400L-P-102	3	3	3	3	3	L
79	400L-P-103	3	3	3	3	3	L
80	400L-P-104	3	3	3	3	3	L
81	400L-P-105A	3	3	3	3	3	L
82	400L-P-105B	3	3	3	3	3	L
83	400L-P-106	3	3	3	3	3	L
84	400L-P-107	3	3	3	3	3	L
85	400L-P-108A	3	3	3	3	3	L
86	400L-P-108B	3	3	3	3	3	L
87	400L-P-109A	3	3	3	3	3	L
88	400L-P-109B	3	3	3	3	3	L

Table 4.1. Consequences Assessment of Pumps in Thailube. (Continued)

Item	Tag	A1	A2	A3	A4	Consequence Rating	Consequence Level
89	400L-P-110A	3	3	3	3	3	L
90	400L-P-110B	3	3	3	3	3	L
91	400L-P-111A	3	3	3	3	3	L
92	400L-P-111B	3	3	3	3	3	L
93	400L-P-112A	3	3	3	3	3	L
94	400L-P-112B	3	3	3	3	3	L
95	400L-P-114A	3	3	3	3	3	L
96	400L-P-114B	3	3	3	3	3	L
97	400L-P-115	3	3	3	1	1	H
98	400L-P-116A	3	3	3	3	3	L
99	400L-P-116B	3	3	3	3	3	L
100	400L-P-117A	3	3	3	3	3	L
101	400L-P-117B	3	3	3	3	3	L
102	400L-P-118A	3	3	3	3	3	L
103	400L-P-118B	3	3	3	3	3	L
104	400L-P-201A	3	3	3	3	3	L
105	400L-P-201B	3	3	3	3	3	L
106	400L-P-202A	3	3	3	3	3	L
107	400L-P-202B	3	3	3	3	3	L
108	400L-P-203A	3	3	3	3	3	L
109	400L-P-203B	3	3	3	3	3	L
110	400L-P-204A	3	3	3	3	3	L
111	400L-P-204B	3	3	3	3	3	L
112	400L-P-301A	3	3	3	3	3	L
113	400L-P-301B	3	3	3	3	3	L
114	400L-P-302A	3	3	3	3	3	L
115	400L-P-302B	3	3	3	3	3	L
116	400L-P-303A	3	3	3	3	3	L

Table 4.1. Consequences Assessment of Pumps in Thailube. (Continued)

Item	Tag	A1	A2	A3	A4	Consequence Rating	Consequence Level
117	400L-P-303B	3	3	3	3	3	L
118	400L-P-401	3	3	3	1	1	H
119	400L-P-501A	3	3	3	3	3	L
120	400L-P-501B	3	3	3	3	3	L
121	400L-P-501C	3	3	3	3	3	L
122	400L-P-501D	3	3	3	3	3	L
123	400L-P-501E	3	3	3	3	3	L
124	400L-P-511A	3	3	3	3	3	L
125	400L-P-511B	3	3	3	3	3	L
126	400L-P-521A	3	3	3	3	3	L
127	400L-P-521B	3	3	3	3	3	L
128	400L-P-601A	3	3	3	3	3	L
129	400L-P-601B	3	3	3	3	3	L
130	400L-P-601C	3	3	3	3	3	L
131	400L-P-602A	3	3	3	3	3	L
132	400L-P-602B	3	3	3	3	3	L
133	400L-P-611A	3	3	3	3	3	L
134	400L-P-611B	3	3	3	3	3	L
135	500L-P-101A	2	3	3	3	2.7	L
136	500L-P-101B	2	3	3	3	2.7	L
137	500L-P-103A	3	3	3	3	3	L
138	500L-P-103B	3	3	3	3	3	L
139	500L-P-104A	3	3	3	3	3	L
140	500L-P-104B	3	3	3	3	3	L
141	500L-P-105A	3	3	3	3	3	L
142	500L-P-105B	3	3	3	3	3	L
143	500L-P-106A	3	3	3	3	3	L
144	500L-P-106B	3	3	3	3	3	L

Table 4.1. Consequences Assessment of Pumps in Thailube. (Continued)

Item	Tag	A1	A2	A3	A4	Consequence Rating	Consequence Level
145	500L-P-108	3	3	3	1	1	H
146	500L-P-110A	2	3	2	3	2.3	L
147	500L-P-110B	2	3	2	3	2.3	L
148	500L-P-151A	3	3	3	3	3	L
149	500L-P-151B	3	3	3	3	3	L
150	550L-P-101A	3	3	2	3	2.7	L
151	550L-P-101B	3	3	2	3	2.7	L
152	550L-P-102A	3	3	3	3	3	L
153	550L-P-102B	3	3	3	3	3	L
154	550L-P-103A	3	3	2	3	3	L
155	550L-P-103B	3	3	2	3	3	L
156	550L-P-104	3	3	3	3	3	L
157	550L-P-105	3	3	3	3	3	L
158	550L-P-106	3	3	3	3	3	L
159	550L-P-107	3	3	3	3	3	L
160	550L-P-108A	3	3	3	3	3	L
161	550L-P-108B	3	3	3	3	3	L
162	560L-P-101A	2	3	3	3	2.7	L
163	560L-P-101B	2	3	3	3	2.7	L
164	600L-P-101A	3	3	3	3	3	L
165	600L-P-101B	3	3	3	3	3	L
166	600L-P-102A	3	3	3	3	3	L
167	600L-P-102B	3	3	3	3	3	L
168	600L-P-103A	3	3	3	3	3	L
169	600L-P-103B	3	3	3	3	3	L
170	600L-P-104	3	3	2	3	2.7	L
171	600L-P-105	3	3	3	3	3	L
172	600L-P-106	3	3	3	1	1	H

Table 4.1. Consequences Assessment of Pumps in Thailube. (Continued)

Item	Tag	A1	A2	A3	A4	Consequence Rating	Consequence Level
173	700L-P-101A	3	3	3	3	3	L
174	700L-P-101B	3	3	3	3	3	L
175	700L-P-102A	3	3	3	3	3	L
176	700L-P-102B	3	3	3	3	3	L
177	700L-P-103A	3	3	3	3	3	L
178	700L-P-103B	3	3	3	3	3	L
179	700L-P-301A	3	2	3	3	2.7	L
180	700L-P-301B	3	2	2	3	2.3	L
181	700L-P-302A	3	2	2	3	2.3	L
182	700L-P-302B	3	2	2	3	2.3	L
183	800L-P-101A	3	2	2	3	2.3	L
184	800L-P-101B	3	2	2	3	2.3	L
185	800L-P-102A	3	2	2	3	2.3	L
186	800L-P-102B	3	2	2	3	2.3	L
187	800L-P-106A	3	3	2	3	2.7	L
188	800L-P-106B	3	3	2	3	2.7	L
189	800L-P-106C	3	3	2	3	2.7	L
190	800L-P-108	3	3	2	3	2.7	L
191	800L-P-109A	3	3	2	3	2.7	L
192	800L-P-109B	3	3	2	3	2.7	L
193	800L-P-110	3	3	2	3	2.7	L
194	850L-P-101	2	2	2	1	1	H
195	850L-P-102	2	2	3	1	1	H
196	850L-P-109	2	2	3	1	1	H
197	850L-P-110	3	3	3	3	3	L
198	2900L-P-101A	3	3	3	3	3	L
199	2900L-P-101B	3	3	3	3	3	L
200	3000L-P-101A	2	3	3	3	2.7	L

Table 4.1. Consequences Assessment of Pumps in Thailube. (Continued)

Item	Tag	A1	A2	A3	A4	Consequence Rating	Consequence Level
201	3000L-P-101B	2	3	3	3	2.7	L
202	3000L-P-102A	2	3	3	3	2.7	L
203	3000L-P-102B	2	3	3	3	2.7	L
204	3000L-P-103	2	3	3	1	1	H
205	3000L-P-104A	3	3	3	3	3	L
206	3000L-P-104B	3	3	3	3	3	L
207	3000L-P-105A	3	3	3	3	3	L
208	3000L-P-105B	3	3	3	3	3	L
209	3000L-P-106A	3	3	3	3	3	L
210	3000L-P-106B	3	3	3	3	3	L
211	3000L-P-107A	3	3	3	3	3	L
212	3000L-P-107B	3	3	3	3	3	L
213	3000L-P-109A	3	3	3	3	3	L
214	3000L-P-109B	3	3	3	3	3	L
215	3000L-P-110A	3	3	3	3	3	L
216	3000L-P-110B	3	3	3	3	3	L
217	3000L-P-111	3	3	1	3	2.3	L
218	3000L-P-112	3	3	1	3	2.3	L
219	3000L-P-113	3	3	1	3	2.3	L
220	3000L-P-114	3	3	1	3	2.3	L
221	3000L-P-115A	3	3	3	3	3	L
222	3000L-P-115B	3	3	3	3	3	L
223	3600L-P-101A	2	3	3	3	2.7	L
224	3600L-P-101B	2	3	3	3	2.7	L
225	3600L-P-101C	2	3	3	3	2.7	L
226	3600L-P-102A	2	3	3	3	2.7	L
227	3600L-P-102B	2	3	3	3	2.7	L
228	3600L-P-102C	2	3	3	3	2.7	L

Table 4.1. Consequences Assessment of Pumps in Thailube. (Continued)

Item	Tag	A1	A2	A3	A4	Consequence Rating	Consequence Level
256	6200L-P-103B	3	3	3	3	3	L
257	6200L-P-105A	3	3	3	3	3	L
258	6200L-P-105B	3	3	3	3	3	L
259	6200L-P-107A	3	3	3	3	3	L
260	6200L-P-107B	3	3	3	3	3	L
261	6200L-P-108A	3	3	3	3	3	L
262	6200L-P-108B	3	3	3	3	3	L
263	6200L-P-109A	3	3	3	3	3	L
264	6200L-P-109B	3	3	3	3	3	L
265	6300L-P-101	3	3	3	3	3	L
266	6300L-P-102	3	3	3	3	3	L
267	6300L-P-103	3	3	3	3	3	L
268	6300L-P-104	3	3	3	3	3	L

Note: A1 = Production Impact

A2 = Safety Impact

A3 = Environmental Impact

A4 = Commercial Impact

4.2.1 The Probability of Failure of Pumps

As per the questionnaires of probability of failure of pumps, the probability of failure for each pump can be listed as following table:

Table 4.2. Probability Failure Assessment of Pumps in Thailube.

Item	Tag	B1	B2	B3	B4	B5	B6	Probability Rating	Probability Level
1	100L-P-101A	3	3	3	3	3	3	3	L
2	100L-P-101B	3	3	3	3	3	3	3	L
3	100L-P-102A	3	3	3	3	3	3	3	L
4	100L-P-102B	3	3	3	3	3	3	3	L
5	100L-P-103A	3	3	3	3	3	3	3	L
6	100L-P-103B	3	3	3	3	3	3	3	L
7	100L-P-104A	3	3	3	3	3	3	3	L
8	100L-P-104B	3	3	3	3	3	3	3	L
9	100L-P-105A	2	2	3	3	3	3	2	M
10	100L-P-105B	2	2	3	3	3	3	2	M
11	100L-P-106A	2	2	3	3	3	3	2	M
12	100L-P-106B	2	2	3	3	3	3	2	M
13	100L-P-107A	2	2	3	3	3	3	2	M
14	100L-P-107B	2	2	3	3	3	3	2	M
15	100L-P-108A	2	2	3	3	3	3	2	M
16	100L-P-108B	2	2	3	3	3	3	2	M
17	100L-P-109A	2	2	3	3	3	3	2	M
18	100L-P-109B	2	2	3	3	3	3	2	M
19	100L-P-110A	2	2	3	3	3	3	2	M
20	100L-P-110B	2	2	3	3	3	3	2	M
21	100L-P-111A	2	2	3	3	3	3	2	M
22	100L-P-111B	2	2	3	3	3	3	2	M
23	100L-P-112A	3	3	3	3	3	3	3	L
24	100L-P-112B	3	3	3	3	3	3	3	L
25	100L-P-113A	3	3	3	3	3	3	3	L
26	100L-P-113B	3	3	3	3	3	3	3	L
27	100L-P-121A	3	3	3	3	3	3	3	L

Table 4.2. Probability Failure Assessment of Pumps in Thailube. (Continued)

Item	Tag	B1	B2	B3	B4	B5	B6	Probability Rating	Probability Level
28	100L-P-121B	3	3	3	3	3	3	3	L
29	200L-P-101A	3	3	3	3	3	3	3	L
30	200L-P-101B	3	3	3	3	3	3	3	L
31	200L-P-102A	3	3	3	3	3	3	3	L
32	200L-P-102B	3	3	3	3	3	3	3	L
33	200L-P-103A	3	3	3	3	3	3	3	L
34	200L-P-103B	3	3	3	3	3	3	3	L
35	200L-P-104A	3	3	3	3	3	3	3	L
36	200L-P-104B	3	3	3	3	3	3	3	L
37	200L-P-105A	2	3	3	3	3	3	2	M
38	200L-P-105B	2	3	3	3	3	3	2	M
39	200L-P-106A	3	3	3	3	3	3	3	L
40	200L-P-106B	3	3	3	3	3	3	3	L
41	200L-P-107A	1	3	3	3	3	3	1	H
42	200L-P-107B	1	3	3	3	3	3	1	H
43	200L-P-108	2	3	3	3	3	3	2	M
44	300L-P-101A	2	2	3	3	3	3	2	M
45	300L-P-101B	2	2	3	3	3	3	2	M
46	300L-P-102A	3	3	3	3	3	3	3	L
47	300L-P-102B	3	3	3	3	3	3	3	L
48	300L-P-103A	3	3	3	3	3	3	3	L
49	300L-P-103B	3	3	3	3	3	3	3	L
50	300L-P-104A	3	3	3	3	3	3	3	L
51	300L-P-104B	3	3	3	3	3	3	3	L
52	300L-P-105A	3	3	3	3	3	3	3	L
53	300L-P-105B	3	3	3	3	3	3	3	L
54	300L-P-106A	3	3	3	3	3	3	3	L
55	300L-P-106B	3	3	3	3	3	3	3	L

Table 4.2. Probability Failure Assessment of Pumps in Thailube. (Continued)

Item	Tag	B1	B2	B3	B4	B5	B6	Probability Rating	Probability Level
56	300L-P-107A	3	3	3	3	3	3	3	L
57	300L-P-107B	3	3	3	3	3	3	3	L
58	300L-P-108A	3	3	3	3	3	3	3	L
59	300L-P-108B	3	3	3	3	3	3	3	L
60	300L-P-109A	3	3	3	3	3	3	3	L
61	300L-P-109B	3	3	3	3	3	3	3	L
62	300L-P-110A	3	3	3	3	3	3	3	L
63	300L-P-110B	3	3	3	3	3	3	3	L
64	300L-P-111A	3	3	3	3	3	3	3	L
65	300L-P-111B	3	3	3	3	3	3	3	L
66	300L-P-112	3	3	3	3	3	3	3	L
67	300L-P-113	3	3	3	3	3	3	3	L
68	300L-P-114A	1	3	3	3	3	3	1	H
69	300L-P-114B	1	3	3	3	3	3	1	H
70	300L-P-115	3	3	3	3	3	3	3	L
71	300L-P-116A	3	3	3	3	3	3	3	L
72	300L-P-116B	3	3	3	3	3	3	3	L
73	300L-P-117	3	3	3	3	3	3	3	L
74	300L-P-151A	3	3	3	3	3	3	3	L
75	300L-P-151B	3	3	3	3	3	3	3	L
76	400L-P-101A	3	3	3	3	3	3	3	L
77	400L-P-101B	3	3	3	3	3	3	3	L
78	400L-P-102	3	3	3	3	3	3	3	L
79	400L-P-103	3	3	3	3	3	3	3	L
80	400L-P-104	3	3	3	3	3	3	3	L
81	400L-P-105A	3	3	3	3	3	3	3	L
82	400L-P-105B	3	3	3	3	3	3	3	L
83	400L-P-106	3	3	3	3	3	3	3	L

Table 4.2. Probability Failure Assessment of Pumps in Thailube. (Continued)

Item	Tag	B1	B2	B3	B4	B5	B6	Probability Rating	Probability Level
84	400L-P-107	3	3	3	3	3	3	3	L
85	400L-P-108A	3	3	3	3	3	3	3	L
86	400L-P-108B	3	3	3	3	3	3	3	L
87	400L-P-109A	3	3	3	3	3	3	3	L
88	400L-P-109B	3	3	3	3	3	3	3	L
89	400L-P-110A	3	3	3	3	3	3	3	L
90	400L-P-110B	3	3	3	3	3	3	3	L
91	400L-P-111A	3	3	3	3	3	3	3	L
92	400L-P-111B	3	3	3	3	3	3	3	L
93	400L-P-112A	3	2	3	3	3	3	2	M
94	400L-P-112B	3	2	3	3	3	3	2	M
95	400L-P-114A	3	3	3	3	3	3	3	L
96	400L-P-114B	3	3	3	3	3	3	3	L
97	400L-P-115	3	3	3	3	3	3	3	L
98	400L-P-116A	3	2	3	3	3	3	2	M
99	400L-P-116B	3	2	3	3	3	3	2	M
100	400L-P-117A	3	3	3	3	3	3	3	L
101	400L-P-117B	3	3	3	3	3	3	3	L
102	400L-P-118A	3	3	3	3	3	3	3	L
103	400L-P-118B	3	3	3	3	3	3	3	L
104	400L-P-201A	3	3	3	3	3	3	3	L
105	400L-P-201B	3	3	3	3	3	3	3	L
106	400L-P-202A	3	3	3	3	3	3	3	L
107	400L-P-202B	3	3	3	3	3	3	3	L
108	400L-P-203A	3	3	3	3	3	3	3	L
109	400L-P-203B	3	3	3	3	3	3	3	L
110	400L-P-204A	3	3	3	3	3	3	3	L
111	400L-P-204B	3	3	3	3	3	3	3	L

Table 4.2. Probability Failure Assessment of Pumps in Thailube. (Continued)

Item	Tag	B1	B2	B3	B4	B5	B6	Probability Rating	Probability Level
112	400L-P-301A	3	3	3	3	3	3	3	L
113	400L-P-301B	3	3	3	3	3	3	3	L
114	400L-P-302A	3	3	3	3	3	3	3	L
115	400L-P-302B	3	3	3	3	3	3	3	L
116	400L-P-303A	3	3	3	3	3	3	3	L
117	400L-P-303B	3	3	3	3	3	3	3	L
118	400L-P-401	3	3	2	3	3	3	2	M
119	400L-P-501A	3	2	3	3	3	3	2	M
120	400L-P-501B	3	2	3	3	3	3	2	M
121	400L-P-501C	3	2	3	3	3	3	2	M
122	400L-P-501D	3	1	3	3	3	3	1	H
123	400L-P-501E	3	1	3	3	3	3	1	H
124	400L-P-511A	3	2	3	3	3	3	2	M
125	400L-P-511B	3	2	3	3	3	3	2	M
126	400L-P-521A	3	2	3	3	3	3	2	M
127	400L-P-521B	3	2	3	3	3	3	2	M
128	400L-P-601A	3	2	3	3	3	3	2	M
129	400L-P-601B	3	2	3	3	3	3	2	M
130	400L-P-601C	3	2	3	3	3	3	2	M
131	400L-P-602A	3	3	3	3	3	3	3	L
132	400L-P-602B	3	3	3	3	3	3	3	L
133	400L-P-611A	3	2	3	3	3	3	2	M
134	400L-P-611B	3	2	3	3	3	3	2	M
135	500L-P-101A	3	3	3	3	3	3	3	L
136	500L-P-101B	3	3	3	3	3	3	3	L
137	500L-P-103A	3	2	3	3	3	3	2	M
138	500L-P-103B	3	2	3	3	3	3	2	M
139	500L-P-104A	3	3	3	3	3	3	3	L

Table 4.2. Probability Failure Assessment of Pumps in Thailube. (Continued)

Item	Tag	B1	B2	B3	B4	B5	B6	Probability Rating	Probability Level
140	500L-P-104B	3	3	3	3	3	3	3	L
141	500L-P-105A	3	3	3	3	3	3	3	L
142	500L-P-105B	3	3	3	3	3	3	3	L
143	500L-P-106A	3	2	3	3	3	3	2	M
144	500L-P-106B	3	2	3	3	3	3	2	M
145	500L-P-108	3	3	3	3	3	3	3	L
146	500L-P-110A	2	3	3	3	2	3	2	M
147	500L-P-110B	2	3	3	3	2	3	2	M
148	500L-P-151A	3	3	3	3	3	3	3	L
149	500L-P-151B	3	3	3	3	3	3	3	L
150	550L-P-101A	3	3	3	3	3	3	3	L
151	550L-P-101B	3	3	3	3	3	3	3	L
152	550L-P-102A	3	3	3	3	3	3	3	L
153	550L-P-102B	3	3	3	3	3	3	3	L
154	550L-P-103A	3	3	3	3	3	3	3	L
155	550L-P-103B	3	3	3	3	3	3	3	L
156	550L-P-104	3	3	3	3	3	3	3	L
157	550L-P-105	3	1	3	3	3	3	1	H
158	550L-P-106	3	1	3	3	3	3	1	H
159	550L-P-107	3	3	3	3	3	3	3	L
160	550L-P-108A	3	3	3	3	3	3	3	L
161	550L-P-108B	3	3	3	3	3	3	3	L
162	560L-P-101A	1	3	3	3	3	3	1	H
163	560L-P-101B	1	3	3	3	3	3	1	H
164	600L-P-101A	3	3	3	3	3	3	3	L
165	600L-P-101B	3	3	3	3	3	3	3	L
166	600L-P-102A	2	3	3	3	3	3	2	M
167	600L-P-102B	2	3	3	3	3	3	2	M

Table 4.2. Probability Failure Assessment of Pumps in Thailube. (Continued)

Item	Tag	B1	B2	B3	B4	B5	B6	Probability Rating	Probability Level
168	600L-P-103A	3	3	3	3	3	3	3	L
169	600L-P-103B	3	3	3	3	3	3	3	L
170	600L-P-104	3	3	3	3	3	3	3	L
171	600L-P-105	3	3	3	3	3	3	3	L
172	600L-P-106	3	3	3	3	3	3	3	L
173	700L-P-101A	3	1	3	3	3	3	1	H
174	700L-P-101B	3	1	3	3	3	3	1	H
175	700L-P-102A	3	3	3	3	3	3	3	L
176	700L-P-102B	3	3	3	3	3	3	3	L
177	700L-P-103A	3	2	3	3	3	3	2	M
178	700L-P-103B	3	2	3	3	3	3	2	M
179	700L-P-301A	3	2	3	3	2	3	2	M
180	700L-P-301B	3	2	3	3	2	3	2	M
181	700L-P-302A	3	2	3	3	3	3	2	M
182	700L-P-302B	3	2	3	3	3	3	2	M
183	800L-P-101A	3	1	1	3	3	3	1	H
184	800L-P-101B	3	1	1	3	3	3	1	H
185	800L-P-102A	3	1	3	3	3	3	1	H
186	800L-P-102B	3	1	3	3	3	3	1	H
187	800L-P-106A	3	1	2	3	3	3	1	H
188	800L-P-106B	3	1	2	3	3	3	1	H
189	800L-P-106C	3	1	2	3	3	3	1	H
190	800L-P-108	3	1	2	3	3	3	1	H
191	800L-P-109A	2	3	3	3	3	3	2	M
192	800L-P-109B	2	3	3	3	3	3	2	M
193	800L-P-110	3	3	3	3	3	3	3	L
194	850L-P-101	3	1	1	3	3	3	1	H
195	850L-P-102	3	1	3	3	3	3	1	H

Table 4.2. Probability Failure Assessment of Pumps in Thailube. (Continued)

Item	Tag	B1	B2	B3	B4	B5	B6	Probability Rating	Probability Level
196	850L-P-109	2	3	3	3	3	3	2	M
197	850L-P-110	3	3	3	3	3	3	3	L
198	2900L-P-101A	3	1	2	3	3	3	1	H
199	2900L-P-101B	3	1	2	3	3	3	1	H
200	3000L-P-101A	3	2	3	3	3	3	2	M
201	3000L-P-101B	3	2	3	3	3	3	2	M
202	3000L-P-102A	3	2	3	3	3	3	2	M
203	3000L-P-102B	3	2	3	3	3	3	2	M
204	3000L-P-103	3	1	3	3	3	3	1	H
205	3000L-P-104A	3	3	3	3	3	3	3	L
206	3000L-P-104B	3	3	3	3	3	3	3	L
207	3000L-P-105A	3	2	3	3	3	3	2	M
208	3000L-P-105B	3	2	3	3	3	3	2	M
209	3000L-P-106A	3	1	3	3	3	3	1	H
210	3000L-P-106B	3	1	3	3	3	3	1	H
211	3000L-P-107A	3	1	3	3	3	3	1	H
212	3000L-P-107B	3	1	3	3	3	3	1	H
213	3000L-P-109A	3	2	3	3	3	3	2	M
214	3000L-P-109B	3	2	3	3	3	3	2	M
215	3000L-P-110A	3	2	3	3	3	3	2	M
216	3000L-P-110B	3	2	3	3	3	3	2	M
217	3000L-P-111	3	1	3	3	3	3	1	H
218	3000L-P-112	3	1	3	3	3	3	1	H
219	3000L-P-113	3	1	3	3	3	3	1	H
220	3000L-P-114	3	1	3	3	3	3	1	H
221	3000L-P-115A	3	3	3	3	3	3	3	L
222	3000L-P-115B	3	3	3	3	3	3	3	L
223	3600L-P-101A	3	2	3	3	3	3	2	M

Table 4.2. Probability Failure Assessment of Pumps in Thailube. (Continued)

Item	Tag	B1	B2	B3	B4	B5	B6	Probability Rating	Probability Level
224	3600L-P-101B	3	2	3	3	3	3	2	M
225	3600L-P-101C	3	2	3	3	3	3	2	M
226	3600L-P-102A	3	2	3	3	3	3	2	M
227	3600L-P-102B	3	2	3	3	3	3	2	M
228	3600L-P-102C	3	2	3	3	3	3	2	M
229	3600L-P-103	3	1	3	3	3	3	1	H
230	3900L-P-101A	3	3	3	3	3	3	3	L
231	3900L-P-101B	3	3	3	3	3	3	3	L
232	3900L-P-101C	3	3	3	3	3	3	3	L
233	3900L-P-101D	3	3	3	3	3	3	3	L
234	3900L-P-102	3	2	2	3	3	3	2	M
235	4200L-P-101A	3	3	3	3	3	3	3	L
236	4200L-P-101B	3	3	3	3	3	3	3	L
237	4200L-P-101C	3	3	3	3	3	3	3	L
238	4400L-P-101A	3	3	3	3	3	3	3	L
239	4400L-P-101B	3	3	3	3	3	3	3	L
240	4500L-P-101A	3	3	3	3	3	3	3	L
241	4500L-P-101B	3	3	3	3	3	3	3	L
242	4500L-P-102A	3	2	3	3	3	3	2	M
243	4500L-P-102B	3	2	3	3	3	3	2	M
244	4500L-P-107A	3	2	3	3	3	3	2	M
245	4500L-P-107B	3	2	3	3	3	3	2	M
246	4500L-P-108A	3	3	3	3	3	3	3	L
247	4500L-P-108B	3	3	3	3	3	3	3	L
248	4700L-P-101A	3	3	3	3	3	3	3	L
249	4700L-P-101B	3	3	3	3	3	3	3	L
250	5900L-P-101	3	3	3	3	3	3	3	L
251	6200L-P-101A	3	1	3	3	3	3	1	H

Table 4.2. Probability Failure Assessment of Pumps in Thailube. (Continued)

Item	Tag	B1	B2	B3	B4	B5	B6	Probability Rating	Probability Level
252	6200L-P-101B	3	1	3	3	3	3	1	H
253	6200L-P-102A	3	3	3	3	3	3	3	L
254	6200L-P-102B	3	3	3	3	3	3	3	L
255	6200L-P-103A	3	1	3	3	3	3	1	H
256	6200L-P-103B	3	1	3	3	3	3	1	H
257	6200L-P-105A	3	1	3	3	3	3	1	H
258	6200L-P-105B	3	1	3	3	3	3	1	H
259	6200L-P-107A	3	1	3	3	3	3	1	H
260	6200L-P-107B	3	1	3	3	3	3	1	H
261	6200L-P-108A	3	2	3	3	3	3	2	M
262	6200L-P-108B	3	2	3	3	3	3	2	M
263	6200L-P-109A	3	3	3	3	3	3	3	L
264	6200L-P-109B	3	3	3	3	3	3	3	L
265	6300L-P-101	2	1	3	3	3	3	1	H
266	6300L-P-102	2	1	3	3	3	3	1	H
267	6300L-P-103	3	2	3	3	3	3	2	M
268	6300L-P-104	3	2	3	3	3	3	2	M

Note: B1 = Seal Failure

B2 = Bearing Failure

B3 = Coupling Failure

B4 = Driver Failure

B5 = Internal Failure

B6 = Pressure Envelope Failure

4.2.3 The Criticality Assessment of Pumps in Thailube

Criticality (risk of failure) is defined as the combination of two parameters, probability of failure and consequence of failure, and is presented in the form of matrix. A 3*3 criticality matrix is used. Therefore, the criticality assessment of pumps in Thailube can be as the following table:

Table 4.3. Criticality Assessment of Pumps in Thailube.

Item	Tag	Consequence Level	Probability Level	Criticality Rating
1	100L-P-101A	L	L	N
2	100L-P-101B	L	L	N
3	100L-P-102A	L	L	N
4	100L-P-102B	L	L	N
5	100L-P-103A	L	L	N
6	100L-P-103B	L	L	N
7	100L-P-104A	L	L	N
8	100L-P-104B	L	L	N
9	100L-P-105A	L	M	L
10	100L-P-105B	L	M	L
11	100L-P-106A	L	M	L
12	100L-P-106B	L	M	L
13	100L-P-107A	L	M	L
14	100L-P-107B	L	M	L
15	100L-P-108A	L	M	L
16	100L-P-108B	L	M	L
17	100L-P-109A	L	M	L
18	100L-P-109B	L	M	L
19	100L-P-110A	L	M	L
20	100L-P-110B	L	M	L

Table 4.3. Criticality Assessment of Pumps in Thailube. (Continued)

Item	Tag	Consequence Level	Probability Level	Criticality Rating
21	100L-P-111A	L	M	L
22	100L-P-111B	L	M	L
23	100L-P-112A	L	L	N
24	100L-P-112B	L	L	N
25	100L-P-113A	L	L	N
26	100L-P-113B	L	L	N
27	100L-P-121A	L	L	N
28	100L-P-121B	L	L	N
29	200L-P-101A	L	L	N
30	200L-P-101B	L	L	N
31	200L-P-102A	L	L	N
32	200L-P-102B	L	L	N
33	200L-P-103A	L	L	N
34	200L-P-103B	L	L	N
35	200L-P-104A	L	L	N
36	200L-P-104B	L	L	N
37	200L-P-105A	L	M	L
38	200L-P-105B	L	M	L
39	200L-P-106A	L	L	N
40	200L-P-106B	L	L	N
41	200L-P-107A	L	H	M
42	200L-P-107B	L	H	M
43	200L-P-108	L	M	L
44	300L-P-101A	L	M	L
45	300L-P-101B	L	M	L
46	300L-P-102A	L	L	N
47	300L-P-102B	L	L	N
48	300L-P-103A	L	L	N
49	300L-P-103B	L	L	N

Table 4.3. Criticality Assessment of Pumps in Thailube. (Continued)

Item	Tag	Consequence Level	Probability Level	Criticality Rating
50	300L-P-104A	L	L	N
51	300L-P-104B	L	L	N
52	300L-P-105A	L	L	N
53	300L-P-105B	L	L	N
54	300L-P-106A	L	L	N
55	300L-P-106B	L	L	N
56	300L-P-107A	L	L	N
57	300L-P-107B	L	L	N
58	300L-P-108A	L	L	N
59	300L-P-108B	L	L	N
60	300L-P-109A	L	L	N
61	300L-P-109B	L	L	N
62	300L-P-110A	L	L	N
63	300L-P-110B	L	L	N
64	300L-P-111A	L	L	N
65	300L-P-111B	L	L	N
66	300L-P-112	L	L	N
67	300L-P-113	L	L	N
68	300L-P-114A	L	H	M
69	300L-P-114B	L	H	M
70	300L-P-115	L	L	N
71	300L-P-116A	L	L	N
72	300L-P-116B	L	L	N
73	300L-P-117	H	L	M
74	300L-P-151A	L	L	N
75	300L-P-151B	L	L	N
76	400L-P-101A	L	L	N
77	400L-P-101B	L	L	N
78	400L-P-102	L	L	N

Table 4.3. Criticality Assessment of Pumps in Thailube. (Continued)

Item	Tag	Consequence Level	Probability Level	Criticality Rating
79	400L-P-103	L	L	N
80	400L-P-104	L	L	N
81	400L-P-105A	L	L	N
82	400L-P-105B	L	L	N
83	400L-P-106	L	L	N
84	400L-P-107	L	L	N
85	400L-P-108A	L	L	N
86	400L-P-108B	L	L	N
87	400L-P-109A	L	L	N
88	400L-P-109B	L	L	N
89	400L-P-110A	L	L	N
90	400L-P-110B	L	L	N
91	400L-P-111A	L	L	N
92	400L-P-111B	L	L	N
93	400L-P-112A	L	M	L
94	400L-P-112B	L	M	L
95	400L-P-114A	L	L	N
96	400L-P-114B	L	L	N
97	400L-P-115	H	L	M
98	400L-P-116A	L	M	L
99	400L-P-116B	L	M	L
100	400L-P-117A	L	L	N
101	400L-P-117B	L	L	N
102	400L-P-118A	L	L	N
103	400L-P-118B	L	L	N
104	400L-P-201A	L	L	N
105	400L-P-201B	L	L	N
106	400L-P-202A	L	L	N
107	400L-P-202B	L	L	N

Table 4.3. Criticality Assessment of Pumps in Thailube. (Continued)

Item	Tag	Consequence Level	Probability Level	Criticality Rating
108	400L-P-203A	L	L	N
109	400L-P-203B	L	L	N
110	400L-P-204A	L	L	N
111	400L-P-204B	L	L	N
112	400L-P-301A	L	L	N
113	400L-P-301B	L	L	N
114	400L-P-302A	L	L	N
115	400L-P-302B	L	L	N
116	400L-P-303A	L	L	N
117	400L-P-303B	L	L	N
118	400L-P-401	H	M	H
119	400L-P-501A	L	M	L
120	400L-P-501B	L	M	L
121	400L-P-501C	L	M	L
122	400L-P-501D	L	H	M
123	400L-P-501E	L	H	M
124	400L-P-511A	L	M	L
125	400L-P-511B	L	M	L
126	400L-P-521A	L	M	L
127	400L-P-521B	L	M	L
128	400L-P-601A	L	M	L
129	400L-P-601B	L	M	L
130	400L-P-601C	L	M	L
131	400L-P-602A	L	L	N
132	400L-P-602B	L	L	N
133	400L-P-611A	L	M	L
134	400L-P-611B	L	M	L
135	500L-P-101A	L	L	N
136	500L-P-101B	L	L	N

Table 4.3. Criticality Assessment of Pumps in Thailube. (Continued)

Item	Tag	Consequence Level	Probability Level	Criticality Rating
137	500L-P-103A	L	M	L
138	500L-P-103B	L	M	L
139	500L-P-104A	L	L	N
140	500L-P-104B	L	L	N
141	500L-P-105A	L	L	N
142	500L-P-105B	L	L	N
143	500L-P-106A	L	M	L
144	500L-P-106B	L	M	L
145	500L-P-108	H	L	M
146	500L-P-110A	L	M	L
147	500L-P-110B	L	M	L
148	500L-P-151A	L	L	N
149	500L-P-151B	L	L	N
150	550L-P-101A	L	L	N
151	550L-P-101B	L	L	N
152	550L-P-102A	L	L	N
153	550L-P-102B	L	L	N
154	550L-P-103A	L	L	N
155	550L-P-103B	L	L	N
156	550L-P-104	L	L	N
157	550L-P-105	L	H	M
158	550L-P-106	L	H	M
159	550L-P-107	L	L	N
160	550L-P-108A	L	L	N
161	550L-P-108B	L	L	N
162	560L-P-101A	L	H	M
163	560L-P-101B	L	H	M
164	600L-P-101A	L	L	N
165	600L-P-101B	L	L	N

Table 4.3. Criticality Assessment of Pumps in Thailube. (Continued)

Item	Tag	Consequence Level	Probability Level	Criticality Rating
166	600L-P-102A	L	M	L
167	600L-P-102B	L	M	L
168	600L-P-103A	L	L	N
169	600L-P-103B	L	L	N
170	600L-P-104	L	L	N
171	600L-P-105	L	L	N
172	600L-P-106	H	L	M
173	700L-P-101A	L	H	M
174	700L-P-101B	L	H	M
175	700L-P-102A	L	L	N
176	700L-P-102B	L	L	N
177	700L-P-103A	L	M	L
178	700L-P-103B	L	M	L
179	700L-P-301A	L	M	L
180	700L-P-301B	L	M	L
181	700L-P-302A	L	M	L
182	700L-P-302B	L	M	L
183	800L-P-101A	L	H	M
184	800L-P-101B	L	H	M
185	800L-P-102A	L	H	M
186	800L-P-102B	L	H	M
187	800L-P-106A	L	H	M
188	800L-P-106B	L	H	M
189	800L-P-106C	L	H	M
190	800L-P-108	L	H	M
191	800L-P-109A	L	M	L
192	800L-P-109B	L	M	L
193	800L-P-110	L	L	N
194	850L-P-101	H	H	E

Table 4.3. Criticality Assessment of Pumps in Thailube. (Continued)

Item	Tag	Consequence Level	Probability Level	Criticality Rating
195	850L-P-102	H	H	E
196	850L-P-109	H	M	H
197	850L-P-110	L	L	N
198	2900L-P-101A	L	H	M
199	2900L-P-101B	L	H	M
200	3000L-P-101A	L	M	L
201	3000L-P-101B	L	M	L
202	3000L-P-102A	L	M	L
203	3000L-P-102B	L	M	L
204	3000L-P-103	H	H	E
205	3000L-P-104A	L	L	N
206	3000L-P-104B	L	L	N
207	3000L-P-105A	L	M	L
208	3000L-P-105B	L	M	L
209	3000L-P-106A	L	H	M
210	3000L-P-106B	L	H	M
211	3000L-P-107A	L	H	M
212	3000L-P-107B	L	H	M
213	3000L-P-109A	L	M	L
214	3000L-P-109B	L	M	L
215	3000L-P-110A	L	M	L
216	3000L-P-110B	L	M	L
217	3000L-P-111	L	H	M
218	3000L-P-112	L	H	M
219	3000L-P-113	L	H	M
220	3000L-P-114	L	H	M
221	3000L-P-115A	L	L	N
222	3000L-P-115B	L	L	N
223	3600L-P-101A	L	M	L

Table 4.3. Criticality Assessment of Pumps in Thailube. (Continued)

Item	Tag	Consequence Level	Probability Level	Criticality Rating
224	3600L-P-101B	L	M	L
225	3600L-P-101C	L	M	L
226	3600L-P-102A	L	M	L
227	3600L-P-102B	L	M	L
228	3600L-P-102C	L	M	L
229	3600L-P-103	L	H	M
230	3900L-P-101A	L	L	N
231	3900L-P-101B	L	L	N
232	3900L-P-101C	L	L	N
233	3900L-P-101D	L	L	N
234	3900L-P-102	L	M	L
235	4200L-P-101A	L	L	N
236	4200L-P-101B	L	L	N
237	4200L-P-101C	L	L	N
238	4400L-P-101A	L	L	N
239	4400L-P-101B	L	L	N
240	4500L-P-101A	L	L	N
241	4500L-P-101B	L	L	N
242	4500L-P-102A	L	M	L
243	4500L-P-102B	L	M	L
244	4500L-P-107A	L	M	L
245	4500L-P-107B	L	M	L
246	4500L-P-108A	L	L	N
247	4500L-P-108B	L	L	N
248	4700L-P-101A	L	L	N
249	4700L-P-101B	L	L	N
250	5900L-P-101	L	L	N
251	6200L-P-101A	L	H	M
252	6200L-P-101B	L	H	M

Table 4.3. Criticality Assessment of Pumps in Thailube. (Continued)

Item	Tag	Consequence Level	Probability Level	Criticality Rating
253	6200L-P-102A	L	L	N
254	6200L-P-102B	L	L	N
255	6200L-P-103A	L	H	M
256	6200L-P-103B	L	H	M
257	6200L-P-105A	L	H	M
258	6200L-P-105B	L	H	M
259	6200L-P-107A	L	H	M
260	6200L-P-107B	L	H	M
261	6200L-P-108A	L	M	L
262	6200L-P-108B	L	M	L
263	6200L-P-109A	L	L	N
264	6200L-P-109B	L	L	N
265	6300L-P-101	L	H	M
266	6300L-P-102	L	H	M
267	6300L-P-103	L	M	L
268	6300L-P-104	L	M	L

Note: N = Negligible

L = Low

M = Medium

H = High

E = Extreme

As the result of criticality assessment, it has been found that the criticality of pumps in Thailube can be distinguished into 5 levels:

(1) There are 142 pumps in N level.

(2) There are 76 pumps in L level.

(3) There are 45 pumps in M level.

(4) There are 2 pumps in H level.

(5) There are 3 pumps in E level.

4.3 An Inventory Model for Mechanical Seals at Thai Lube Base Refinery

As the data from criticality assessment, the management agreed that the inventory for the criticality in E and H level should be kept at our warehouse for 100%, but the inventory for the criticality in N level should be ignored.

For the criticality in N, H and E level, after the data was analyzed, it was found that the inventory for mechanical seals in Thailube are only 5 sets of mechanical seals.

For the criticality in L and M level, the total pumps in these levels are 121 pumps. The inventory model for these levels should be considered to MTBF and lead time.

The lead time for receiving mechanical seal is 2 months.

The MTBF data of pumps in criticality L and M level is as the following table:

Table 4.4. MTBF for Pump in Criticality L and M.

Item	Tag	MTBF (months)
1	100L-P-105A	NA
2	100L-P-105B	NA
3	100L-P-106A	NA
4	100L-P-106B	NA
5	100L-P-107A	NA
6	100L-P-107B	36
7	100L-P-108A	NA
8	100L-P-108B	36
9	100L-P-109A	NA

Table 4.4. MTBF for Pump in Criticality L and M. (Continued)

Item	Tag	MTBF (months)
10	100L-P-109B	NA
11	100L-P-110A	36
12	100L-P-110B	36
13	100L-P-111A	NA
14	100L-P-111B	NA
15	200L-P-105A	18
16	200L-P-105B	36
17	200L-P-107A	NA
18	200L-P-107B	NA
19	200L-P-108	NA
20	300L-P-101A	36
21	300L-P-101B	NA
22	300L-P-114A	NA
23	300L-P-114B	NA
24	300L-P-117	18
25	400L-P-112A	NA
26	400L-P-112B	36
27	400L-P-115	36
28	400L-P-116A	NA
29	400L-P-116B	NA
30	400L-P-501A	NA
31	400L-P-501B	NA
32	400L-P-501C	36
33	400L-P-501D	NA
34	400L-P-501E	NA
35	400L-P-511A	NA
36	400L-P-511B	NA
37	400L-P-521A	NA
38	400L-P-521B	NA

Table 4.4. MTBF for Pump in Criticality L and M. (Continued)

Item	Tag	MTBF (months)
39	400L-P-601A	NA
40	400L-P-601B	NA
41	400L-P-601C	NA
42	400L-P-611A	NA
43	400L-P-611B	NA
44	500L-P-103A	NA
45	500L-P-103B	NA
46	500L-P-106A	36
47	500L-P-106B	12
48	500L-P-108	NA
49	500L-P-110A	NA
50	500L-P-110B	36
51	550L-P-105	NA
52	550L-P-106	36
53	560L-P-101A	6
54	560L-P-101B	6
55	600L-P-102A	36
56	600L-P-102B	NA
57	600L-P-106	NA
58	700L-P-101A	NA
59	700L-P-101B	NA
60	700L-P-103A	NA
61	700L-P-103B	NA
62	700L-P-301A	36
63	700L-P-301B	12
64	700L-P-302A	36
65	700L-P-302B	36
66	800L-P-101A	NA
67	800L-P-101B	NA

Table 4.4. MTBF for Pump in Criticality L and M. (Continued)

Item	Tag	MTBF (months)
68	800L-P-102A	NA
69	800L-P-102B	36
70	800L-P-106A	NA
71	800L-P-106B	NA
72	800L-P-106C	NA
73	800L-P-108	NA
74	800L-P-109A	6
75	800L-P-109B	12
76	2900L-P-101A	NA
77	2900L-P-101B	NA
78	3000L-P-101A	NA
79	3000L-P-101B	NA
80	3000L-P-102A	36
81	3000L-P-102B	NA
82	3000L-P-105A	NA
83	3000L-P-105B	36
84	3000L-P-106A	NA
85	3000L-P-106B	NA
86	3000L-P-107A	NA
87	3000L-P-107B	NA
88	3000L-P-109A	NA
89	3000L-P-109B	NA
90	3000L-P-110A	NA
91	3000L-P-110B	NA
92	3000L-P-111	NA
93	3000L-P-112	NA
94	3000L-P-113	NA
95	3000L-P-114	NA
96	3600L-P-101A	NA

Table 4.4. MTBF for Pump in Criticality L and M. (Continued)

Item	Tag	MTBF (months)
97	3600L-P-101B	NA
98	3600L-P-101C	NA
99	3600L-P-102A	NA
100	3600L-P-102B	NA
101	3600L-P-102C	NA
102	3600L-P-103	NA
103	3900L-P-102	NA
104	4500L-P-102A	NA
105	4500L-P-102B	NA
106	4500L-P-107A	NA
107	4500L-P-107B	NA
108	6200L-P-101A	NA
109	6200L-P-101B	NA
110	6200L-P-103A	NA
111	6200L-P-103B	NA
112	6200L-P-105A	NA
113	6200L-P-105B	NA
114	6200L-P-107A	NA
115	6200L-P-107B	NA
116	6200L-P-108A	NA
117	6200L-P-108B	NA
118	6300L-P-101	NA
119	6300L-P-102	NA
120	6300L-P-103	18
121	6300L-P-104	36

Note: NA = Pump has not failed since operating.

From the above table, only 29 pumps have ever failed since operating. The 92 remaining pumps have not failed before that means the reliability of these pumps is very good. Therefore, the inventory for the mechanical seal of these pumps should not be set.

From the classical EOQ inventory model, the 29 pumps can be considered as following:

K = Set up cost = 100 bahts per order

h = Holding cost = 5% * 150,000 = 7,500 bahts per year

For example, 100L-P-107B - MTBF = 36 Months

From the data above, we have:

D = 0.03 unit per Month

K = 100 bahts per order

h = 7,500 bahts per year = 625 bahts per Month

L = 2 Months

Thus,

y* = sqrt (2KD / h) = sqrt (2*0.03*100 / 625) = 0.1 unit

The associated cycle length is:

t_0* = y*/D = 0.1/0.03 = 3.3 Months

Therefore, the inventory level should be dropped to LD = 2*0.03 = 0.06 unit. But the mechanical seal cannot be divided into many pieces. Therefore, it was recommended to stock the mechanical seal for this pump for 1 set.

For the other 28 pumps, the inventory level was shown in the table:

Table 4.5. Inventory Model for Pumps.

Item	Tag	MTBF	y*	t_0*	Inventory Level (unit)
1	100L-P-107B	36	0.1	3.3	0.06 = 1

V. CONCLUSIONS

5.1 Research Summary

The inventory model of mechanical seal in Thailube has already been set. It can reduce the inventory of mechanical seal from 268 sets to 34 sets. The cost of inventory mechanical seal also was reduced around 35,100,000 bahts.

The method for implementation of inventory model of mechanical seal are the following steps:

(1) List the equipment that were used in Thailube.

(2) Study the criticality assessment theory. The criticality assessment of equipment is defined as the combination of two parameters, probability of failure and consequence of failure, and is presented in the form of matrix.

(3) Set the criteria of consequence of failure. There are four criteria for this research that are production impact, safety impact, environmental impact and commercial impact.

(4) Gather the criteria of probability of failure for equipment. In this research, the pump was focused because mechanical seal is the one component of the pump. There are six failure modes for pump to assess that are seal failure, bearing failure, coupling failure, driver failure, internal failure and pressure envelope failure.

(5) Assess the equipment according to the criteria of consequence of failure and probability of failure one by one. The team to assess the equipment were included of operator, engineer, and technologist. In this process, the team must ensure that all relevant information such as process data, engineering design, standard and etc. are captured.

(6) Evaluate the criticality of equipment by using the 3*3 matrix that combined two parameters – probability of failure and consequence of failure. The criticality levels were distinguished into 5 levels that are N = Negligible, L = Low, M = Medium, H = High, E = Extreme.

(7) Set the inventory model according to management policy.

Not only was the inventory model got, but also the maintenance work can be prioritize before doing the work because each equipment didn't have the same criticality. However, the productivity and reliability of plant was still good.

5.2 Future Research

According to the result of this research, the inventory cost of mechanical seal was reduced around 35,100,000 bahts. Therefore, it was recommended to do the inventory model for other equipment by using the criticality assessment and inventory model.

Moreover, the mechanical seal was composed of many parts such as stationary seal ring, rotary seal ring, and etc. Parts of one equipment can be interchanged with parts of the other equipment because of the same material and dimension. Each part has different lead time and cost. It will be more effective inventory model of mechanical seal, if the component parts of the mechanical seal were carried out as the inventory model instead of the whole set of mechanical seal. Therefore, it was recommended to further carry out inventory model of mechanical seal by focusing on the component parts of the mechanical seal.

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