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RISK-BASED DESIGN MARGIN SELECTION FOR HEAT EXCHANGERS

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ABSTRACT

For more than a quarter century, business and industry have used risk-based matrices to quantify probability and consequences in decision making. However, this tool has not yet been applied to the heat exchanger design process. Adding a *design margin* to the calculated size of an exchanger is common practice. This margin represents the added heat exchanger area necessary to provide confidence that the exchanger will operate as required throughout its run cycle. An assumption is made that the additional area will not have a deleterious impact on performance.

This report introduces the concept of a *risk-based design margin* selection process as a quantitative aid in separating the individual components that comprise the uncertainty in heat exchanger design. In addition, it provides a technique to help the designer determine a reasonable, cost-effective margin to apply to the heat exchanger. Two example cases show the application of the procedure.

RISK ASSESSMENT AND ITS APPLICABILITY TO HEAT EXCHANGER DESIGN

Risk assessment was first officially described in 1983 by the U.S. National Research Council in a paper titled, “Risk Assessment in the Federal Government: Managing the Process.” Initially applied to assist in describing health risks, risk assessment was later used to manage many different government functions by quantifying the acceptable risk and prioritizing possible dangers. This system was quickly adopted by industry, as well as by food and health agencies, in the United States and other countries.

In the petroleum industry, for example, the American Petroleum Institute (API) provides guidance for developing a risk-based inspection program for fixed equipment and piping in refineries [0002]. Also, the National Aeronautics and Space Administration (NASA) uses risk analysis to manage project and technical risks, as well as safety issues, by seeking to anticipate and address uncertainties that threaten critical aspects of each area. The uncertainties can range from questions of material and parts quality in a project to exploring risk from the chemical, engineering, or reliability concerns that may pose a threat to personnel, equipment, the public, and the environment [2008].

Risk assessment is easily adapted to any technology. Here we suggest a standard form that can be applied in the decision-making process for identifying design margin in a heat exchanger.

Heat exchanger designers must consider many input parameters and assumptions, including all the fluid properties and conditions under which the exchanger is expected to operate. These assumptions attempt to establish all possible maintenance, energy, and margin factors that constrain the equipment selection for the design. All these parameters and suppositions have varying degrees of influence on the exchanger design and can differ widely for similar equipment in a plant, or even within the same operating unit.

Because of the potential variability and uncertainty in these parameters, a tradition has evolved that adds surface area to the exchanger, thus buying “insurance” to increase the confidence that the exchanger will operate as required. The problem is that this insurance (commonly known as *fouling factor* or *fouling resistance*) has become the catch-all for many factors that together increase the uncertainty of the heat exchanger design. Fouling resistances are selected from independent sources such as the TEMA *Standards* [2007], plant data, company standards, or simple safety factors. Although adding fouling resistance is intended to enable an exchanger to perform its required duty at the end of its run cycle, it may create fouling due to excess surface area at the beginning of the run cycle.

Many of these resistance values, created in the early half of the twentieth century, have never been updated for current design practice and are now obsolete. The application of fouling factors in the petroleum industry often wastes resources, and in some cases, the effect of the added area has become “a self-fulfilling prophecy” [Hays, 1989], causing fouling that would otherwise not have occurred [Müller-Steinhagen, 2000].

Improper selection of the design margin can produce significant changes in the purchase price of a heat exchanger and in its subsequent operating costs, sometimes more than doubling these costs. In 2004, Nesta and Bennett presented a new perspective on a design method that addresses the effects of heat exchanger fouling. Currently developed for liquid hydrocarbons with API gravity < 45 and cooling water, their "no-foul" design method offers practical guidelines to reduce fouling in these services. Once fouling unknowns are eliminated, margin can be applied primarily for design and operation uncertainties. In 2007, Bennett, Kistler, Lestina, and King described the application of the Nesta-Bennett design method for an actual exchanger that reduced the exchanger cost by 23 – 33 percent.

HTRI formed the Exchanger Design Margin Task Force (EDMTF) to develop a new approach to *design margins*. This report introduces a *risk-based design margin matrix* for selecting the appropriate error scaling factor, fouling resistance, and project uncertainty. The quantitative probabilities and consequences can be modified to apply to specific equipment design parameters and operating assumptions that vary by plant and unit.

APPLYING RISK ANALYSIS MATRIX TO HEAT EXCHANGER DESIGN

We recommend using the risk matrix to shift from a low-confidence, self-fulfilling, *fouling factor*-type approach to a quantitative, technical, risk-based approach. Using a design margin risk matrix, heat exchanger designers can base the addition of extra area to the design on key contributing components, a function of

- the statistical errors in the predictive correlations
- naturally occurring conditions that degrade performance
- project-specific uncertainties

Risk Analysis Matrix

A typical risk matrix is a five-by-five grid as shown in Figure 1, with the top right corner representing the highest risk and the bottom left corner the lowest risk.

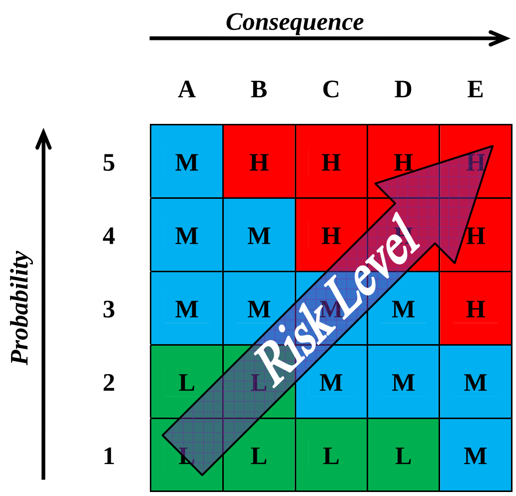

Fig. 1 Standard risk-based matrix.

The two parameters of the risk matrix are the probability and the consequence.

Probability Parameters: Potential frequency of an event. Probability parameters describe the likelihood of an event occurring. The step change of these parameters is designed to range from the highly unlikely (level 1 in our scale) to near certainty (level 5 in our scale) that something will occur within a specific time frame. The values can be based on a purely theoretical probability or on actual experiences, but they should be vetted so that they realistically represent the chance of occurrence. Probability here refers to the likelihood of the heat exchanger failing to perform its function due to the associated uncertainty of correlation, fouling, or operation.

Consequence Parameters: Financial or other consequence. The consequence parameters are meant to realistically represent the impact of an event's occurrence (e.g., in our case, the consequences arising from the heat exchanger failing to perform its function in the plant where it operates). The consequences can vary in type and magnitude from site to site, and do not have to be negative. Therefore, consequence parameters should be developed independently for each process plant; these parameters require detailed input from and close collaboration with the plant owners. It is critical that the consequences be adequately defined so that they reflect the impact on all facets of the exchanger operation—from cost effectiveness to safety awareness. The parameters should be prioritized by order of consequences. Here they are labeled from A through E. Level A consequences are relatively insignificant, such as a minimal financial impact or very small safety risk. Level E consequences could include plant failure, significant damages or lost sales, or loss of life.

Initial cost is affected by several parameters, including materials, exchanger type, number of shells, and components. However, when considering the cost consequences of a heat exchanger, the user should account for the total installed cost (TIC), which is often two to four times the capital cost of the exchanger alone. Many factors may affect the TIC:

- location of the exchanger
  Installing a large exchanger on an upper platform is often more expensive than putting one at ground level.
- associated installation costs for piping, foundations, insulation, and instrumentation
- pressure rating of the exchanger
  Increasing the size of a high pressure exchanger is more costly than a low pressure one.

The matrix presents regions of risk level in probability/consequence combinations (e.g., 1/A through 5/E). As shown in Figure 1, H (high risk - red), M (medium risk - blue), and L (low risk - green) designate these regions.

Risks in the H level require immediate attention; they *must* be mitigated because they are high in both probability and consequence and are unacceptable for long-term operation. M risks should be dealt with when possible. L risks are acceptable because they are unlikely, or if they do occur, are not very significant. Ideally, designers would like to mitigate all problems until the heat exchanger parameters occupy this region.

Design Margin Redefined

We define *design margin* as the additional heat exchanger size required to compensate for three parameters:

1. **Correlational Error**
   Uncertainty inherent in correlations used to predict heat transfer performance
   This parameter can make the exchanger larger or smaller than needed if the design is based on heat transfer correlations that have no error tolerance included. Such uncertainty ranges from ±5 percent to ± 30 percent for most cases, but is sometimes as high as ±100 percent or more where little or no information exists.
2. **Fouling Resistance**
   Expectation that fouling will occur over the life of the heat exchanger
   Fouling resistance is the additional heat transfer resistance that may develop over the time that the exchanger is operational. Often a value is included that covers the other uncertainties described here in items 1 and 3, even when no fouling is expected. We propose to use a value for fouling resistance *only* if the risk level for fouling is high enough to justify it.
3. **Operating Uncertainty**
   Unknowns associated with project conditions
   This component of the design margin is based on the overall uncertainty associated with the project in which the exchanger is to be commissioned. For example, if this is a new type of exchanger or if it is used in a new process (where flow conditions or true stream thermo-physical properties may be in question), the designer may want to increase its size to ensure that it can perform the required duty. But if this is a common service or a retrofit in which the operating conditions are well known, no additional margin is required for this category.

DEVELOPMENT OF RISK MATRIX FOR DESIGN MARGIN SELECTION

The following tables provide qualitative and quantitative criteria used to determine both probability and consequence for each of the parameters contributing to the overall design margin.

Using the design margin risk matrix requires identifying

- a probability value for each of the three design margin components: correlation error (**Corr**), fouling resistance (**Fouling**), and operating uncertainty (**Oper**)
- a consequence value, representing failure of the exchanger

Our application of the risk matrix assumes that the consequence is the same for all three probability values. The combination of these probabilities and consequence reflects the risk level: low (**L**), medium (**M**), or high (**H**). For each of these levels, the risk matrix suggests actions for each design margin component.

Table 1. Probabilities

Probability	Correlation Error	Fouling	Operating Uncertainty
1	Error less than or equal to +/- 6%	No fouling in this service at this plant or any other plant; probability: 1 in 100 years	No change from existing
2	Error less than or equal to +/- 17%	Minimal in this service in this and other plants caused by unusual circumstances; probability: 1 in 50 years	20% change from existing
3	Error less than or equal to +/- 37%	Fouling at this and other plants, but not run-limiting; probability: 1 in 25 years	50% change from existing
4	Error less than or equal to +/- 62%	Heavy fouling in this service, limiting run length to shorter than planned; probability: 1 in 10 years	100% change from existing
5	Error greater than +/- 62%	Severe fouling (run-limiting) in this same service at this plant; probability: 1 in 2 years (frequent)	New service never applied before

Table 2. Consequences

Consequence	
A	Heat exchanger is 100% spared. If totally fouled, minimal to no impact; cost < US$100 thousand
B	Heat exchanger can be bypassed with minimal impact on throughput; US$100 thousand < cost < US$1 million
C	Fouling causes slowdown of unit but operation continues with additional furnace duty; US$1 million < cost < US$10 million
D	Fouling leads to shutdown of unit; US$10 million < cost < US$100 million
E	Fouling leads to shutdown of plant; cost > US$100 million

Table 3. Suggested Action at Indicated Risk Level

Risk Level	Correlation Error*	Fouling	Operating Uncertainty
L	Apply 0.95 scaling to *h*	Do not apply fouling factor, but add 5% extra area	Do not apply a duty multiplier
M	Apply 0.85 scaling to *h*	Apply traditional fouling factor, but reduce as necessary so that total fouling resistance is less than 20% of the overall resistance or zero fouling factor	Apply 1.1 duty factor
H	Apply 0.75 scaling to *h*	Monitor existing unit performance, prepare a root-cause analysis for the fouling experience, and select optimum design fouling/cleaning schedule based on findings	Apply 1.2 duty factor

**h* = Calculated heat transfer coefficient ** Risk Number = Probability/Consequence

EXAMPLE CASES

Although not based on actual cases, these two examples show how the design margin risk matrix can be applied to typical process heat exchanger applications.

Example 1: Refrigeration Service

The heat exchanger being designed for a refrigeration service at a chemical plant has the same streams as an existing unit that has operated successfully for 25 years.

The refrigerant is propane vaporizing on the shell side. The existing service has seen little fouling; consequently, the exchanger was cleaned only once, after a leak allowed oil to enter the system. Subsequently, gas seals were installed, and no further fouling has been observed on the propane side.

The tubeside fluid is a vapor stream being cooled with no condensation occurring. The gas is clean, and the existing exchanger has no history of fouling on the gas side at any time. We use the matrix to identify the probabilities, consequences, and risk level for this example**.**

Probabilities.

- Correlation Error (**Corr**): The heat transfer correlations used for this service have an estimated error of ±15 percent. They were used to check the performance of the existing exchanger during the last measured run and matched the data very well. We estimate the probability of the new heat exchanger failing to meet the predicted performance because of correlation error as 2.
- Fouling Resistance (**Fouling**): The existing heat exchanger has a history of no-to-minimal fouling over a long period of time. The sole minor fouling experience was caused by an event that has been mitigated by the installation of gas seals. We estimate the probability of the new exchanger failing to meet the predicted performance because of fouling as 2.
- Operating Uncertainty (**Oper**): The new heat exchanger will operate in a service that is identical to one that has run successfully for many years. No changes are planned in operation. We estimate the probability of the exchanger requiring additional duty due to operating uncertainty as 1.

Consequences. The consequences to the unit operation for this case are estimated as level B because the exchanger can be bypassed with an impact on the unit of approximately US$20000 per day and a replacement bundle can be obtained within two weeks for an estimated total potential financial loss of US$280000.

Risk Level. The risk level is Low for all three probability parameters:

- Corr = 2/B
- Fouling = 2/B
- Oper = 1/B

	A	B	C	D	E
5	M	H	H	H	H
4	M	M	H	H	H
3	M	M	M	M	H
2	L	L	M	M	M
1	L	L	L	L	M

The matrix suggests applying a 0.95 scaling factor to the heat transfer coefficients, using zero fouling resistance with an additional 5 percent area, and not adding a duty multiplier. The additional area should be added in a manner that results in minimum impact on lowering the velocity.

Example 2: Crude Oil Heater

This example considers an existing heat exchanger in the hot end of the preheat train operating with crude oil on the tube side and a hot pump-around stream on the shell side. A review of the operating data for the past two years shows that a history of fouling that required cleaning this exchanger every two months. The exchanger can be bypassed, but doing so can cause a unit slowdown when the fired heater reaches its firing limit; the results are extra energy expense due to additional firing of the heater and margin loss when the heater firing limit is reached. The engineering department has been asked to investigate replacing the exchanger because of damage that has occurred during the frequent cleanings. We use the matrix to identify the probabilities, consequences, and risk level for this example**.**

Probabilities.

- Correlation Error (**Corr**): The heat transfer correlations used for this service have an estimated error of ±30% based on data from the last measured run. The probability of the exchanger failing to meet the predicted performance because of correlation error is estimated as level 3.
- Fouling Resistance (**Fouling**): Over a two-year period, the heat exchanger has a history of severe, frequent fouling. Because the fuel used for firing is expensive and the existing furnace firing capacity is limited, the impact was costly. The probability of the exchanger failing to meet the predicted performance because of fouling is estimated as level 5.
- Operating Uncertainty (**Oper**): The heat exchanger in this case is a direct replacement of one for which the duty is known. No changes in operation are planned. The probability of the exchanger requiring additional duty due to uncertainty of operation is estimated as level 1.

Consequences. Depending on the degree of fouling in the other hot-end exchangers, their impact on the furnace, and the knowledge that the exchanger can be cleaned and replaced in service within 10 days, a consequence cost of US$1.5 million is estimated. The consequence to the unit operation for this case is estimated as level C.

Risk Level:

- Medium for Corr = 3/C
- High for Fouling = 5/C
- Low for Oper = 1/C

	A	B	C	D	E
5	M	H	H	H	H
4	M	M	H	H	H
3	M	M	M	M	H
2	L	L	M	M	M
1	L	L	L	L	M

For this case, the matrix recommendation is controlled by the High rating for Fouling. Consideration should also be given to the Medium rating for Correlation Error by applying a scaling factor on the calculated heat transfer coefficient. Because there is little operating uncertainty, no duty multiplier is needed.

Recognizing the fouling risk is only the first step. The next step should be to develop a list of ways to mitigate the fouling probability, e.g., checking the existing design in a rigorous computer model to identify excessively low velocity zones and/or high wall temperatures. A different type of exchanger, different baffling, and/or online cleaning technologies need to be evaluated based on their potential to decrease the fouling probability parameter to at least the medium or, if possible, the low level.

The same approach to changes in geometry or operating conditions could potentially move the operation into a region with a higher confidence level (lower correlation error).

Afterwards, the new risk level should be reviewed before work commences on a new design.

CONCLUSIONS

Risk analysis has become a very effective tool in the petroleum and other related industries to arrive at cost-effective decisions. Yet current design practices routinely add excess area to heat exchanger designs. Using a more systematic approach to design margin can reduce not only initial and total installed costs but also operating expenses such as energy usage. In addition, efficient exchanger performance minimizes maintenance while increasing run times.

The well-accepted risk analysis approach provides designers with quantitative indicators for setting important design parameters. The results of this study support further work to improve the probability parameters for different types of exchangers and multiple applications.

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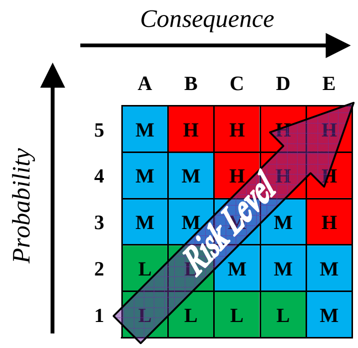

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Risk Matrix for Design Margin Selection