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Intelligent Algorithm-Based Risk Assessment Modeling Method for Liquid Carbon Dioxide Unloading in Shipboard Carbon Capture Systems

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Abstract Onboard Carbon Capture System (OCCS) realizes carbon emission reduction of ships by capturing carbon dioxide (CO_2) exhaust gas generated during ship navigation and liquefying and storing it until it is offloaded ashore for professional treatment. Since the offloading of liquid carbon dioxide (LCO_2) has a certain risk, and the operation is complicated and requires high professional technology, this paper launches a research on the risk assessment method of liquid carbon dioxide offloading. Based on the storage conditions of LCO_2 in the shipboard carbon capture system and the unloading method and process, we analyze the content of the unloading risk assessment and the acceptable level. A fuzzy system is introduced to accurately reflect the degree and level of liquid carbon dioxide offloading risk and form a liquid carbon dioxide offloading risk assessment method. Collect the risk data in the actual unloading process of liquid carbon dioxide, and use the fuzzy system method to calculate the unloading risk data set. Based on this dataset, an offloading risk assessment model is proposed by combining the BP neural network algorithm. After training and iteration, the model has an accuracy rate of 95%, and the loss value is maintained at a very low level of 0.099, which shows an excellent risk assessment capability.

Index Terms shipboard carbon capture system, liquid carbon dioxide unloading, risk assessment, BP neural network, fuzzy system

I. Introduction

Ship shipping is the main global mode of cargo movement, and maritime transport accounts for more than 80% of global transportation, occupying a crucial position in international and domestic transportation [1], [2]. However, CO_2 emissions caused by ship fuel combustion have caused irreversible environmental hazards to the global ecosystem, and the greenhouse effect caused by it poses a serious threat to human production and life [3]-[5]. Therefore, reducing pollutant emissions from ships has become a technical challenge to be solved in the process of green and low-carbon transformation of ships [6]. Based on the increasingly severe carbon emission reduction situation in the shipping industry, shipboard carbon capture technology, which focuses on the short- to medium-term and matures in the medium- to long-term, has emerged to provide a full-cycle solution for the green and low-carbon development of the shipping industry [7], [8].

Realizing GHG emission reduction from ships involves replacing fossil fuels with low-carbon alternative fuels or reducing the carbon intensity of existing fuels, both of which face many challenges. Some progress has been made in the development of viable alternative fuels such as green or blue methanol, ammonia, and hydrogen energy. Literature [9] reviewed and evaluated alternative energy technologies that can reduce GHG emissions during maritime transportation operations, among which biofuels have a significant potential for application in achieving sustainable development goals. Literature [10] examines the possible differences affecting the choice of alternative energy sources for the maritime industry sector in the short or long term, based on an understanding of the characteristics and potential of alternative fuels to maximize the applicability of alternative fuels for use by the shipping industry in different scenarios. Literature [11] describes the production methods of green alternative energy sources for the shipping industry, by emphasizing that technological research and development capabilities and fuel production efficiency are key tasks to ensure adequate fuel supply and advance carbon reduction in the shipping industry. Literature [12] compares the effectiveness of numerous marine alternative fuels leading to low or zero carbon, including conventional heavy fuel oil fuels, blue alternative fuels produced from natural gas, and green fuels based on biomass and solar energy, which informs the choices of stakeholders involved in decarbonizing shipping. Literature [13] shows that methanol is a cost effective, less disruptive and highly infrastructure compatible fuel alternative for the shipping industry, and its use as a marine blended fuel can facilitate a rapid green transition in the shipping industry. Literature [14] proposed a large ship propulsion system using ammonia as an alternative fuel, which solves the problem of ammonia decomposition to generate power and NOx emission as a by-product, and ultimately realizes zero CO2 emission in ship transportation. Literature [15] examined the effect of green hydrogen energy in the shipping industry from various aspects, by comparing the cost of hydrogen energy production and the degree of greenhouse gas emissions in different production routes, to provide the best solution to reduce the pressure of greenhouse gas emissions from maritime transportation. However, the practical application of these fuels to the shipping industry will take time and may be costly, which is a limitation at this stage.

While shipboard carbon capture technology neither reduces the consumption of fuel nor requires the change of alternative fuels, but achieves the compliance of carbon emissions from ships on the basis of the use of traditional fossil fuels, which is an important means to reduce carbon dioxide emissions in the future, to ensure energy security, to build an ecological civilization and to achieve sustainable development. Literature [16] points out that the application of ship carbon capture technology in the shipping industry can achieve faster carbon emission reduction results, and further analyzes the technical feasibility of the ship carbon capture system, aiming to promote the development of carbon capture and storage technology for major shipping ships. Literature [17] used simulation to illustrate the cost competitiveness advantage of shipboard carbon capture (SBCC) technology over alternative fuel methods, and the cost per ton of CO_2 captured by SBCC technology is much less than the cost of alternative fuels under the same conditions, and it can also reduce the CO_2 emissions in a short period of time. Literature [18] carried out a techno-economic evaluation of different carbon capture technologies for medium-range tankers, and simulation experiments showed that amine-based solvent absorption is the best ship carbon capture method under the same ship conditions and evaluation criteria. Literature [19] designed an innovative multi-objective approach to assess the sustainability of carbon capture and storage technologies on board ships, and constructed a performance assessment model based on specific indicators to provide a highly efficient and sustainable strategy for carbon emission reduction in the shipping industry. Literature [20] analyzed the principles, advantages, and applicability conditions of carbon capture and storage methods for ships, and showed that CO_2 storage in solid and liquid states is a feasible option, but the solid storage technology is not yet commercially mature, and the liquid CO_2 storage shows higher feasibility in terms of energy consumption and cost. Literature [21] discusses the safety and integrity challenges inherent in shipboard carbon capture and storage technologies, contributing to an increased understanding of the technical hazards, risks, and safety considerations that can lead to health and sustainability in the carbon reduction process. The aforementioned studies both describe the advantages of implementing shipboard carbon capture technology and highlight the risks and limitations associated with the technology, with a focus on the risks of offloading liquid carbon dioxide from shipboard carbon capture systems.

This paper firstly describes in detail the storage requirements, offloading methods and processes of liquid carbon dioxide in the shipboard carbon capture system. Then, based on the definition of risk, it describes the steps of risk assessment for liquid CO2 offloading process, as well as the different possible risks and acceptable risk levels. At the same time, a fuzzy system is introduced to calculate the level of different risks in the liquid carbon dioxide unloading process, and the design of the unloading risk assessment method is completed. Subsequently, with reference to the actual unloading operation process, a part of the risk evaluation data set is calculated and the unloading risk assessment model based on BP neural network is constructed. Finally, the actual risk assessment application of the model is carried out.

II. OCCS LCO_2 unloading method and process

II. A. CO_2 storage conditions on board ships

The CO_2 triple-phase point is about 517 kPa, -56°C, and the critical point is about 7380 kPa, 31.3°C. Storage of LCO_2 below the triple-phase point should be avoided due to the impurity sensitivity and/or sensitivity to small temperature or pressure changes, which can result in a phase change from liquid to solid CO_2, which can lead to pressure build-up and pipeline blockage. In order to facilitate the storage and unloading of CO_2, typical storage methods for CO_2 captured on board are semi-cooled C-tanks and ISO tank containers, with the storage conditions shown in Table 1.

Table 1: Typical storage conditions for CO_2 on board ships

Shipboard storage system		Storage temperature (°C)	Storage pressure (kPa)	Working pressure (kPa)
Semi-cooled C tank	Low pressure storage	-54.3~-40.1	570~1000	800
	High pressure storage	-30.5~-21.2	1400~1900	1600
ISO tank container		-25.0~-20.0	1800~2400	2200

II. B.LCO$_2$ unloading method

There are three typical OCCS LCO$_2$ offloading methods, namely ship-to-liquid bulk terminal offloading, ship-to-ship offloading, and ISO tank container to container terminal offloading. The advantages and disadvantages of the different offloading methods are shown in Table 2.

Table 2: Advantages and disadvantages of typical OCCS LCO$_2$ unloading methods

Unloading mode	Advantage	Disadvantage
The ship unloaded at the liquid bulk terminal	Can make full use of the liquid bulk terminal cargo handling facilities	The liquid bulk terminal has restrictions on the type and size of the vessel unloading vessel, and also has an impact on the operation plan of the liquid bulk terminal
Ship-to-ship unloading	It can save the port time of the unloading ship, and there are not too many restrictions on the unloading type and size, and LCO$_2$ can be unloaded on a large scale	The initial investment in the construction of CO2 receiving vessels is large and the cost recovery cycle is long
ISO tank containers unloaded at container terminal	The initial investment is small, and the port container cargo unloading facilities are common	Not suitable for large CO$_2$ offloads

II. C.LCO$_2$ unloading process

Ship management companies shall collect ports where LCO$_2$ can be offloaded and give full consideration to the demand for LCO$_2$ offloading when formulating vessel voyage plans. Before arriving at the LCO$_2$ offloading port, the ship should contact the agent and receiving unit in advance to confirm the LCO$_2$ offloading plan, formulate the offloading operation plan, and entrust the agent or receiving unit to apply for the relevant formalities with the competent maritime authorities. After the ship arrives at the port, a multi-party briefing meeting is held with the receiving unit and the terminal (berthing and unloading). After that, the ship connects the relevant unloading equipment and pipelines, and starts unloading after safety inspection. After unloading, the ship carries out pipeline cleaning, dismantles the pipelines, measures the work and completes the unloading.

III. Methodology for assessing the risk of unloading liquid carbon dioxide

III. A. Overview of risk assessment theory

III. A. 1) Definition of risk

From the safety point of view, the risk is the possibility of bringing harm to the personnel due to the occurrence of accidents in a certain period of time, i.e., the risk depends not only on the frequency of the occurrence of dangerous accidents, but also on the magnitude of the consequences caused by the accidents. At present, the risk of an event of the system R with the probability of occurrence of the event P and the consequences of the event amplitude C of the two indicators to express. That is, the risk of the system can be expressed as equation (1):

$$R = \sum_i (f_i \times c_i) \tag{1}$$

III. A. 2) Risk assessment content and process

Risk assessment is to identify and evaluate risks and make a comprehensive and integrated analysis. The main content contains hazard identification, event probability analysis, accident consequence calculation, accident risk reduction measures research and other work. Risk assessment mainly addresses four aspects:

(1) What are the possible accidental risk events.
(2) What is the probability of occurrence of accidental risk events.
(3) What is the severity of the consequences of an accidental risk event once it occurs.
(4) Whether the risk is accepted.

Overall, the assessment process can be divided into two phases, i.e., the pre-data preparation phase and the post quantitative assessment phase. Data preparation includes: determining safety objectives, defining safety criteria, system description and hazard identification. Quantitative risk assessment is carried out after the completion of the above work, which is the core part of this paper, including the assessment of the probability of hazardous events and the evaluation of the consequences of hazardous events, and the risk assessment process is shown in Fig. 1.

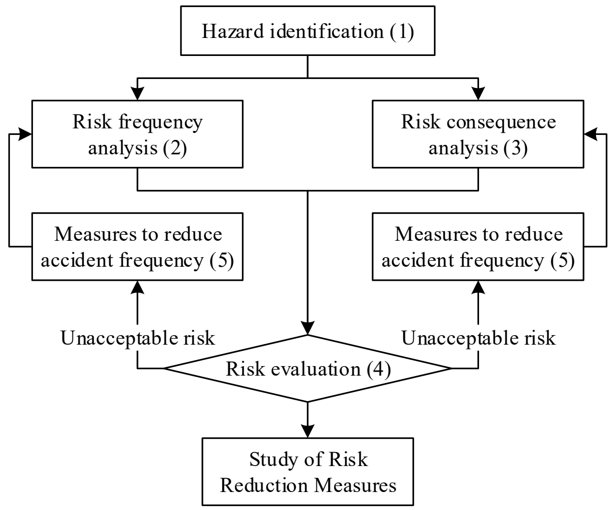


Figure 1: The general process of risk assessment

III. A. 3) Risk acceptance criteria

The damage of accidents is mainly reflected in three aspects: casualties, property damage and environmental pollution, so there are different criteria for measuring risk. In the process of risk assessment, the following three aspects are mainly considered in the measurement of risk: personnel risk (group risk, individual risk), environmental risk and property risk. At present, in the assessment of security for quantitative risk assessment generally use personnel risk as a measurement indicator.

(1) Personnel risk

Personnel risk is commonly represented by group risk value (PLL), individual risk value (IRPA) and risk frequency - casualty curve ($f-N$ curve).

a) Group risk value (PLL)

Group Risk Value (PLL): It measures the risk of the operation to the company, industry, or society, and measures the risk faced by a group of people as a whole. Societal risk can be expressed in a variety of ways, but for liquid carbon dioxide offloading facilities the most commonly used is the "potential for death". PLL is defined as the long-term value of the number of deaths per year, and in the QRA analysis, PLL is calculated by Equation (2):

$$PLL = \sum_N \sum_J f_{nj} \times c_{nj} \tag{2}$$

where, f_{nj} : annual incidence of accidents with incidental events n with human consequences of j, c_{nj} : the annual number of fatalities for the eventuality n with a human consequence of j, N : total number of accidents in all event trees (top events in the event tree), J : type of consequence for all personnel risks, including immediate death, escape, evacuation, and rescue.

b) Individual Risks $(IRPA)$

Personal risk $(IRPA)$ refers to the "annual risk to an individual". This metric takes into account the average time a person is exposed to risk, and based on the level of staffing on the platform, the value of $IRPA$ is estimated as in equation (3):

$$IRPA = \frac{PLL}{POB_{ev}} \times \frac{H}{8760} \tag{3}$$

Where, POB_{ev} : denotes the average annual staffing number, H : indicates the number of hours per person per year at risk, $IRPA$: its value indicates the fatal risk that each person may encounter on the ship's platform.

c) $f-N$.

Both the $f-N$ curve and the group risk value can be used to represent the hazard posed by an incident to an overall population, which is a curve that represents the relationship between the frequency of an incident and the number of fatalities caused by the incident. While the risk of death is measured by the individual risk, in the case of liquid carbon dioxide offloading, there is also a concern about the consequences of the accident for society as a whole. Therefore, in many cases, it is necessary to find the sum of the risks to the whole society, i.e. the group risk. The group risk can be visualized by the $f-N$ curve, and the combination of the $f-N$ curve with the risk criterion makes it straightforward to determine whether the risk is acceptable or not.

(2) Environmental risk

The degree of damage to the environment from an over-oxygenation or expansion explosion of liquid carbon dioxide can be measured in terms of its recovery time, which can generally be categorized as follows: 1 month to 12 months, 1 year to 3 years, 3 years to 10 years, and >10 years. The risk criteria for acceptable environmental risk are shown in Table 3.

Table 3: Environment risk acceptable risk criteria (ratio 5% can be ignored)

Environmental damage level	Average recovery time (a)	Acceptable frequency limits
Less	1/2	0.1
Medium	2	0.023
Great	5	0.01
Serious	20	0.0025

(3) Property risk

Property risk usually refers to damage to materials and production delays. Damage to material can be categorized as localized damage, single and multi-module damage, and overall damage. Product delays, on the other hand, can be categorized by the duration of the delay, such as a day's delay, a few days, and so on.

Life safety is the most important element of risk. If the unloading process is not handled correctly, there is a high risk of liquid carbon dioxide leakage, resulting in excessive oxygen isolation and potential toxicity volatilization, which can lead to significant toxicological symptoms or even more serious consequences for the operator.

III. B. Fuzzy systems

The theoretical foundation of fuzzy system is based on fuzzy set theory and fuzzy logic theory. Fuzzy set theory is the foundation of fuzzy system theory, which extends the traditional “yes” and “no” in binary logic into a continuous and fuzzy concept to better describe uncertainty and ambiguity. In fuzzy set theory, the degree of association of an element with a set is determined by a certain degree of affiliation, and this degree of affiliation reflects the fuzzy affiliation between the element and the set. On the other hand, fuzzy logic theory is the reasoning basis of fuzzy system. Traditional Boolean logic can only deal with “true” and “false” propositions, while fuzzy logic allows the truth value of propositions to be any value between $[0,1]$, which enables better interpretation of uncertainty and ambiguity of information. Based on fuzzy set theory and fuzzy logic theory, fuzzy system realizes the processing and analysis of fuzzy information through the steps of fuzzification, fuzzy rule base, fuzzy inference and fuzzy defuzzification.

Fuzzy refers to the “neither here nor there” or “uncertainty” in objective things, for example, whether the risk level of liquid carbon dioxide unloading is safer or slightly more dangerous, etc., for the expression of language is generally stereotypical, but the degree of expression is fuzzy. This ambiguity is more common in indicators for evaluating the emergency response capacity of a risk. In order to cope with this ambiguity, the obtained qualitative results of the evaluation indicators are entered into the fuzzy system for preprocessing. The main role is to defuzzify the qualitative evaluation indicators. This process includes determining the weights of the indicators, establishing the set of states of the indicators and assigning a score to each state. Then, the fuzzy system will calculate the scores of each level of indicators as well as the expected results, so as to realize the transformation and precision of the evaluation.

The classification of the risk level of liquid carbon dioxide offloading from ships into five levels I, II, III, IV and V, which correspond to the five offloading risk levels of very low, low, average, high and extra high, respectively, is a language with great ambiguity. In the field of risk assessment, describing the degree of safety level of the assessment object is mostly related to quantitative concepts, and the fuzzy system can precisely quantify the qualitative degree described by adjectives.

When combining the fuzzy system and the width learning system, it is necessary to carry out the fuzzification weighting process for the information stored in the mapped to the feature nodes and the enhancement nodes, so that the information can maintain the fuzziness in the transmission process, and the fuzzy logic neuron function expression is shown in Eqs. (4)-(5):

$$u_i = F_i\left(x_1, x_2, \cdots, x_n, v_{i1}, v_{i2}, \cdots, v_{in}\right) \tag{4}$$

$$y_i = f_i\left(u_i\right) \tag{5}$$

where $x_1, x_2, \cdots, x_n$ are the fuzzy system inputs. $v_{i1}, v_{i2}, \cdots, v_{in}$ are the weights of each neuron. F_i is the fuzzy logic function. u_i is the fuzzy neuron state. f_i is the fuzzy system output function. y_i is the fuzzy system output.

When the fuzzy system input is $x = \left(x_{11}, x_{12}, \cdots, x_{1j}; x_{21}, x_{22}, \cdots, x_{2j}; \cdots; x_{i1}, x_{i2}, cdots, x_{ij}\right)$, and the set of linguistic variable values is shown in equation (6):

$$L(x_i) = \left\{A_i^1, A_i^2, \cdots, A_i^j\right\} \tag{6}$$

where x_i is a fuzzy linguistic variable.

Let A_i^j be the j th neuron variable of x_i, which is defined as a fuzzy set over x_i, then the affiliation function is as in equation (7):

$$f = \mu_{A_i^j}(x_i) \tag{7}$$

The output of the fuzzy system can be obtained as Eqs. (8)-(9) by varying the fuzzy weighting rules:

$$\begin{cases} y_1 = x_{11}p_1 + x_{12}p_2 + \cdots + x_{1j}p_j \\ y_2 = x_{21}p_1 + x_{22}p_2 + \cdots + x_{2j}p_j \\ \vdots \\ y_i = x_{i1}p_1 + x_{i2}p_2 + \cdots + x_{ij}p_j \end{cases} \tag{8}$$

$$y = \left(y_1, y_2, \cdots, y_i\right)^T \tag{9}$$

IV. Construction and Application of Assessment Models

IV. A. Acquisition of data sets

The offloading process of the shipboard carbon capture system mainly consists of: preparation, loading and unloading, and completion. The preparation stage includes: safe connection of loading and unloading pipelines and loading and unloading facilities, assessment of the compatibility of operating devices, confirmation of loading and unloading operating conditions and procedures; the loading and unloading stage includes: loading and unloading pipeline cleaning, loading and unloading operations, loading and unloading replenishment, pressure, temperature and liquid level detection and vapor management; the completion stage includes: loading and unloading pipeline cleaning, inspection, connection, pipeline disconnection, communication disconnection, and communication disconnection. The completion stage includes: loading and unloading pipeline cleaning, inspection, connection, pipeline disconnection, communication disconnection.

Combined with the liquid carbon dioxide unloading process of the shipboard carbon capture system, this paper selects 10 more important indicators in the unloading process: (I1) compatibility of items (including loading and unloading control and safety systems, connectors, emergency response procedures, communication systems, etc.), (I2) meteorological conditions (including visibility, wind direction, and wind speed, etc.), (I3) ship's mooring status, (I4) loading and unloading rate, (I5) replenishment rate , (I6) storage compartment internal pressure, (I7) storage compartment temperature, (I8) storage compartment level, (I9) storage compartment operating working pressure, and (I10) operator protective equipment.

The operational status of the 10 indicators is indicated by the numerical form of 1-5, where 1: completely unsuitable for operation, 2: need to make further adjustments, 3: meet the operational standards, 4: suitable for operation, and 5: completely suitable for operation. Eight practical application scenarios of the current shipborne carbon capture system are selected, and the operational status of the 10 indicators in the eight scenarios is analyzed in Table 4.

The possible liquid carbon dioxide unloading risks were reproduced by selecting each indicator parameter from Table 4, and then a fuzzy comprehensive evaluation was carried out (based on the performance of the operational status, a risk rating of 0-10 was carried out, in which 0-2 was ultra-high risk, 3-4 was high risk, 5-6 was medium risk, 7-8 was low risk, and 9-10 was no risk), and the final partially evaluated dataset obtained is shown in Figure 2.

Table 4: Job status of different indicators

Scene	I1	I2	I3	I4	I5	I6	I7	I8	I9	I10
1	2	1	2	5	5	3	1	2	1	4
2	2	2	3	3	1	2	3	4	1	3
3	4	2	3	5	3	2	4	5	2	1
4	1	1	4	3	1	1	2	2	2	4
5	2	2	3	2	2	1	5	2	2	2
6	4	3	5	4	5	4	4	2	2	4
7	3	4	4	3	4	5	2	5	2	1
8	5	2	4	3	3	3	2	5	4	2

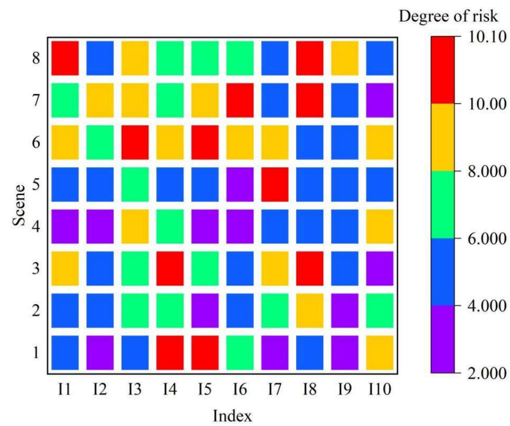
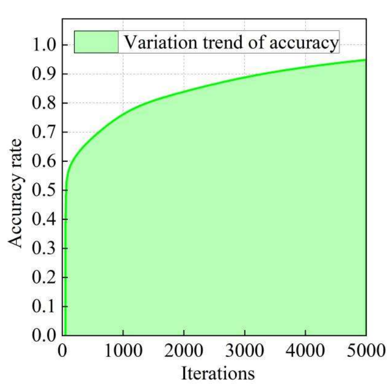


Figure 2: Partial data set

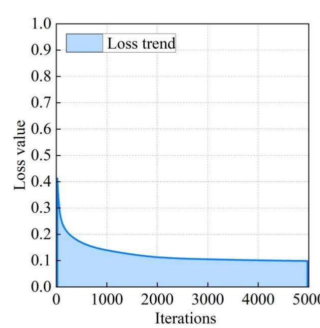
IV. B. Unloading Risk Assessment Model Based on BP Neural Networks

After obtaining the above fuzzy evaluation data, it is necessary to normalize the index parameters and define the fuzzy evaluation results into five types of labels to obtain the dataset of liquid carbon dioxide unloading risk assessment. On the basis of the dataset, the unloading risk assessment model was constructed with the help of Anaconda3 platform and Python3.9 programming language, based on the BP neural network model algorithm.

After dividing the dataset into training set and validation set, the accuracy of the model reaches the maximum value after 5000 times of training selection, and the loss value no longer decreases but tends to be stable, at this time, it is considered that the model training is completed. The accuracy of model training is shown in Fig. 3(a), and the loss value is shown in Fig. 3(b). The accuracy of the trained model on the training set reaches 95%, and the model's classification effect is relatively good. Meanwhile the loss value is stabilized at 0.099, which indicates that the model is robust and the prediction result of the model is close to the expected result to a high degree.



(a) Accuracy rate



(b) Loss value

Figure 3: Model training performance

IV. C. Example validation of liquid carbon dioxide offloading risks

The assessment model designed in this paper is added to a shipborne carbon capture system to focus on the operating pressure of the storage compartment during the loading and unloading operation to verify the effectiveness of the assessment model proposed in this paper. From the content of the second section, it is known that the maximum working pressure of the storage tank is 2200 kPa. Based on the analysis content of the previous subsection, the risk assessment stage of the loading and unloading operation is divided into: (U0) pipeline blowing, (U1) open the pipeline valves, (U2) turn on the pump to unload, (U3) loading and unloading to make up the full amount, (U4) stop the loading and unloading, (U5) deal with the risk, and (U6) resume the loading and unloading. The performance of the assessment model in the actual risk assessment is shown in Figure 4. The first detection of the working pressure in the storage compartment is close to the maximum load-bearing value after opening the pipeline valve, and the second detection of the working pressure in the storage compartment is close to the maximum load-bearing value in the process of opening the pump and unloading when the fault warning is issued, and the measures to stop loading and unloading operations and risk treatment are initiated according to the risk level. The loading and unloading operation will be resumed after the pressure in the storage tank is stabilized at 1400-1800kPa.

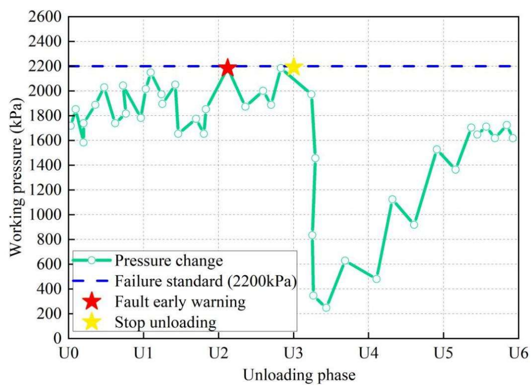


Figure 4: Application examples of evaluation models

After resuming the loading and unloading operation, the unloading risk assessment model collects and uploads a set of data every 15 minutes, calculates the probability of possible risks at that stage, and finally calculates the real-time operational risk status value. The distribution of liquid carbon dioxide unloading risk value assessment based on the risk assessment model in this paper is shown in Figure 5.

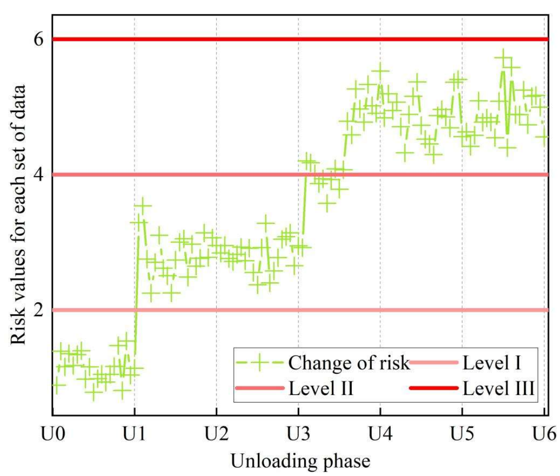


Figure 5: Unload risk assessment distribution

Summarizing the above, the offloading risk assessment model proposed in this paper can effectively quantify the risk value of liquid carbon dioxide offloading in shipboard carbon capture system, carry out risk early warning and give the corresponding risk rating, and assist the corresponding risk management decisions and measures.

V. Conclusion

In this paper, the fuzzy system method is applied to calculate the risk level in the unloading process of shipboard liquid carbon dioxide, and the unloading risk assessment model is established based on the BP neural network algorithm. After 5000 training iterations, the model has a high accuracy rate of 95%, a stable loss value of 0.99, and strong robustness. And in the process of practical application, it can accurately quantify the risk values of different time periods in the unloading process, calculate the corresponding risk assessment, and provide reliable numerical references for relevant decision-making.

By applying the fuzzy comprehensive evaluation algorithm and BP neural network algorithm, this paper has successfully established a reliable and feasible unloading risk assessment model, which provides technical reference for the safe unloading of liquid carbon dioxide from ships.

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