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Structure Maintenance Technology and Risk Based Maintenance (RBM)

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1 Background

In Japan, confidence in safety has been shaken recently by events such as the occurrence of major industrial accidents and the falsification of inspection records. As a mature society, Japan possesses a vast amount of social and industrial infrastructure assets. The time has come for such assets to be carefully maintained and utilized. Under these circumstances, the urgent tasks are a detailed analysis of the reasons for the outbreak of numerous problems despite Japan's strict regulations and the preparation of maintenance technology to keep a safe and secure society.

The deterioration of the structures that comprise the social and industrial infrastructure, declining numbers of preservation-related engineers, inadequate transmission of techniques to new generations, and outdated regulations have been pointed out as causes of problems such as those mentioned above. At the same time, increasingly harsh international competition necessitates cost cutting and efficient plant operation in all manufacturing industries. In other words, it is extremely important that technologies be developed, personnel be trained, and policies be prepared to maintain aging facilities at low cost without compromising safety.

Under these circumstances, recently attention is being paid to the maintenance management method called "risk based maintenance" (RBM), which began in Europe and the USA and utilizes risk (the probability of failure multiplied by the amount of consequence that would be caused by failure) as its standard. Under the RBM method, risk is quantified in order to determine priority for maintenance. Because it reduces unnecessary inspections and prioritizes investment where risk is greater, it is a highly rational method. Since a safe and secure society can be defined as one in which the risk to any structure is below a acceptable level, it is expected that RBM will be established in Japan as well.

In addition, because extending the longevity of social and industrial infrastructure will bring about a massive reduction in garbage, establishing methods for the long-term, safe utilization of existing infrastructure is an urgent task from the point of view of environmental protection as well.

2 The current state of technology related to structure maintenance

Most existing structures utilize concrete and steel as their primary materials. To state the concept another way, a structure that is operated safely is one that is operated without breaking down. When structures fail during use, they do so according to the specific fracture mechanisms of concrete and steel. We have a long history of utilizing those structural materials and many cases of their failure, so it is correct to say that their fracture mechanisms are fully understood.

2-1 Fracture mechanisms

Below I will describe the known fracture mechanisms of concrete and steel.

(1) Concrete fracture

Concrete fracture during use occurs through the mechanisms shown in Table 1, when its

Table 1 : Overview of concrete deterioration mechanisms

Deterioration mechanism	Overview
Carbonation	Concrete bonding declines mainly through the penetration of atmospheric carbon dioxide and rain, causing rebar corrosion and generating cracks in the concrete through expanding rust.
Salt injury	Chloride ions from salt water, etc., penetrate the concrete, causing rebar corrosion and generating cracks in the concrete through expanding rust.
Frost damage	The freezing of moisture within the concrete causes expansion, generating cracks.
Alkali aggregate reaction	If chloride ions are included at the time of manufacture (through use of sea sand, etc.), they react with the aggregate over time, decreasing concrete bonding, causing rebar corrosion, and generating cracks in the concrete through expanding rust.
Chemical erosion	When used in environments where the concrete contacts chemicals, penetration of corrosive materials causes decreased concrete strength and rebar corrosion.
Fatigue	Repeated loads generate cracks in the concrete.

Table 2 : Overview of steel fracture mechanisms

Fracture mechanism		Overview
Fatigue		Loads that would not cause fractures if they were static can bring about fractures if they are repeated. This is called "fatigue fracture." Because fatigue will not occur below a certain level of stress (the fatigue limit) , designs ordinarily are made under the stress that would bring about fatigue. However, unexpected concentrated stresses and so on may cause fatigue. This is the most common of the fracture mechanisms for ferrous materials.
Corrosion	General Corrosion	A uniform surface is contacted by a uniform corrosive agent (chemicals, etc.) and corrosion proceeds uniformly (thinning phenomenon), so corrosion is easy to detect.
	Local corrosion (pitting)	Corrosion proceeds locally through discontinuity in surface shape, non-uniform flow of corrosive agents, etc., so corrosion towards the depth (pitting) is swift. Detection is difficult.
	Stress corrosion cracking (SCC)	Corrosion proceeds in the form of cracks under stress, so cracks develop swiftly. This is the most dangerous corrosion phenomenon. SCC of stainless steel under chloride ions is the best-known type.
Creep		Metal materials that will not distort or fracture under load conditions at normal temperature will distort and fracture over time when above certain temperatures. This is called "creep" (or "creep fracture").
Brittle fractures and corrosion damage caused by deterioration characteristic of materials		At high temperature, the atoms of metal materials move, causing structural changes and degrading the characteristics of the material. After material characteristics have been degraded, fractures may occur even under use conditions met until that point. For example: • Brittle fracture through degraded toughness (tempering, creep embrittlement, 475°C embrittlement, sigma phase embrittlement) following use at high temperature for a specific period. • Corrosion damage through degradation of corrosion resistance (sensitizing, etc.).

strength declines (deteriorates) and it breaks down or flakes under the cyclic load, impact, or earthquake.

(2) Steel fracture

Fracture during use of steel occurs as shown in Table 2.

2-2 Life prediction

Regarding known fracture mechanisms, if fractures can be predicted (when and where they will occur), safe operation is possible. Research and development has been carried out on technology for predicting life based on each type of fracture mechanism.

Among the fracture mechanisms of concrete and steel, prediction (life assessment) of creep for steel is the most advanced. Because creep is inevitable in boilers, turbines, and other equipment used at high temperatures, they are designed to permit it. Life assessments are continually performed while they are in use, thus making life assessment technology indispensable. Life prediction research regarding creep fracture is thus the most advanced. On the other hand, designs attempt to avoid fatigue and corrosion, and research emphasis is placed on methods to prevent their initiation. Life assessment methods regarding fatigue and corrosion are therefore not sufficiently established.

Below I will describe an example of creep life assessment for heating tubes in fossil-fuel power generation boilers. Figure 1 shows the progress of deformation (creep curve) over time of steel boiler tube under a fixed load at high temperature, finally resulting in rupture. The photographs in the chart show the internal structural changes of the materials as creep deformation progresses. Life prediction is to learn what stage of its entire life a member has reached by non-destructive methods. The chart shows how measuring the amount of distortion and the degree of structural change in the steel boiler tube enables us to know its position in its life cycle. Although direct measurement of the amount and degree of distortion of a steel tube is impossible except in special cases, the tube's surface can be ground to observe structural change and ultrasonic can be used to detect voids and microcracks. Methods to assess the life of steel boiler tubes through other parameters (material hardness, precipitation characteristics, electric resistance, etc.) are currently being developed. The Ministry of Economy, Trade and Industry's guidelines for extending the time between periodic inspection of boilers suggests that the inspection period may be extended from two years to four years if detailed prediction through any of the methods shown in Figure 2 confirm sufficient life.

Figure 1 : Schematic of development of creep damage in Cr-Mo steel

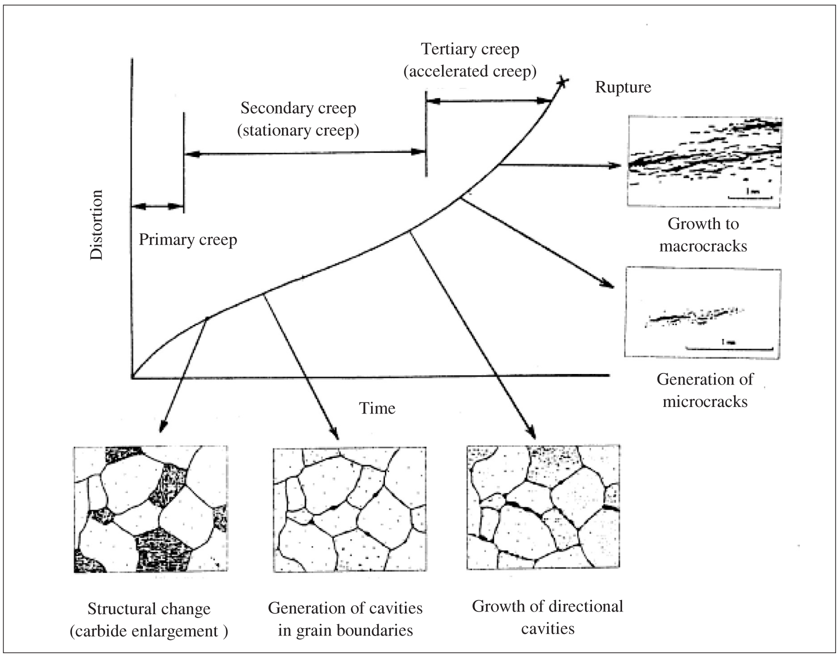


Figure 2 : Non-destructive creep damage assessment methods indicated by guidelines

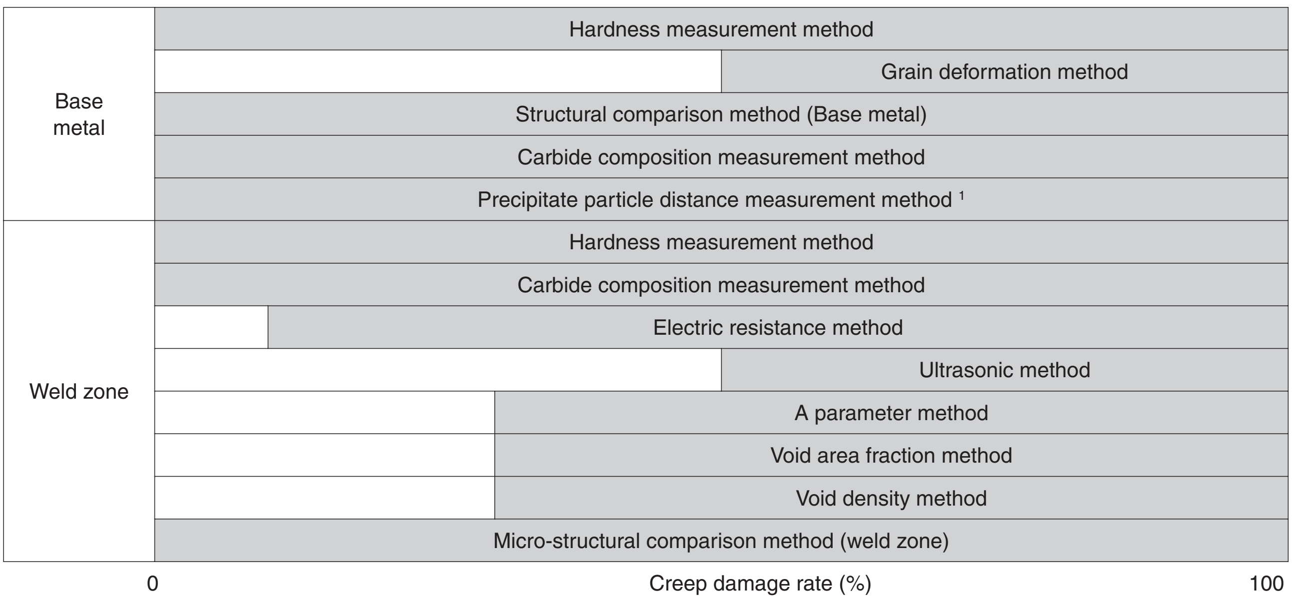
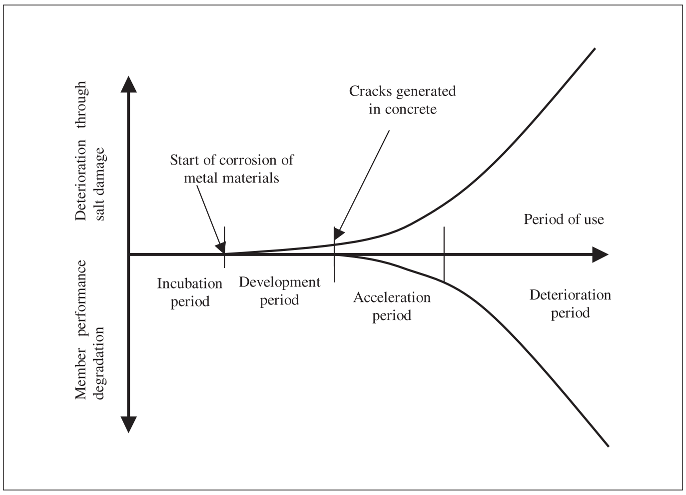


Figure 3 : Model of the process of deterioration due to salt injury



Fossil-fuel power generation boilers are the most advanced example of the use of life assessment methods for preservation and the rational extension of life. Life diagnosis for steel structures in general is quite advanced, but it is desirable that rational preservation be implemented in all social and industrial infrastructure through the establishment of life assessment policies.

Concrete structures are designed with a higher safety factor than steel structures, and with the exception of earthquakes, there are no cases of failure due to deterioration under normal use. Because there is therefore little need for life assessment, research remains inadequate. Figure 3[1] provides a schematic of the process of deterioration through salt injury. The deterioration process is understood qualitatively, but a method to measure the degree of deterioration has yet to be developed. With the number of concrete structures 50 years of age or older to increase in the near future, research and development on life prediction technology is greatly needed.

2-3 Non-technical issues

(1) Human resources responsible for preservation

Safe operation has been made possible by skilled engineers working in design and maintenance. During the period of high economic growth in Japan in the latter half of 1960s, there was a boom in the construction of all types of plants. Many outstanding engineers were involved in their construction, gaining valuable on-site knowledge and experience. Subsequently, they engaged in the maintenance of those plants and supported their safe operation as experts. In research as well, building materials research reached its peak in the 1970s, with many researchers engaged not only in materials development but also research on the fracture mechanisms mentioned above. That led to progress both in explaining mechanisms and in the development of prediction technologies. In recent years, however, plant construction has declined drastically and construction materials development has plateaued. On-site engineers lack opportunities to gain experience, and structural materials research is very quiet. Furthermore, advancing computer measurement and control are leading to the rationalization of sites, and the number of maintenance engineers is declining.

(2) Globalization

In the past, all Japanese social and industrial infrastructure has been designed and built in Japan using domestically manufactured materials. In recent years, however, as the wave of globalization has overtaken Japan, the introduction of foreign products (including materials) is advancing. Most products manufactured in Japan have quality near the upper limits of standards, but those manufactured overseas vary much more widely in quality and include some at minimum standards. For Japan, which has been used to uniformly high-quality products, the safe maintenance of variable products requires a new set of responses.

Specifically, establishment of a database of standards and quality for foreign products is desirable.

3 Recent trends in preservation in Japan and abroad

Japan's nuclear power generation facility maintenance standards were implemented in October 2003. In the past, all defects detected through the inspection in power generation facilities were required to be repaired. Under the new maintenance standards, however, the development of defects over a certain amount of time is predicted, and if the degree of degradation of structural strength meets the safety standards the facility can be operated as is. Actual assessment must meet the Codes for Nuclear Power Generation Facilities (Rules on Fitness-for-Service for Nuclear Power Plants) of the Japan Society of Mechanical Engineers. Detailed analysis is required, but in light of the ill effects of repair welding of tiny flaws (generation of residual stress, etc.), the maintenance standards enable more rational and highly reliable maintenance of nuclear power generation facilities.

In light of that trend, risk based maintenance (RBM; see next section for details), a maintenance management method that uses risk (the probability of failure multiplied by the amount of consequence that would be caused by failure) as its standard, is garnering attention[2].

The establishment of RBM methods requires broad-based research and development related to maintenance, and is drawing great interest from industry and academia. The High Pressure Institute of Japan (HPI) began an RBM research committee three years ago. The maintenance subcommittee of the equipment materials committee of the Society of Chemical Engineers, Japan, is studying RBM. The Engineering Advancement Association of Japan (ENAA) has undertaken a two year project of "feasibility study on the development of RBM methods for optimal maintenance of mechanical systems[3]" beginning in 2003 under contract with Foundation System Research & Development Institute of Japan. Beginning in 2004, the ENAA began a government-commissioned project on "development of advanced maintenance systems for extending the life of industrial and social capital structures." In fiscal 2004, the Japan Society for the Promotion of Science established a leadership research and development committee on "risk-based preservation technologies for chemical plants."

Overseas, the American Petroleum Institute (API) published guidelines for risk-based inspection (RBI)[4,5] in oil refineries and promotes the spread of RBI. The American Society of Mechanical Engineers (ASME) also publishes RBI guidelines for various types of plants[6]. Europe as a whole is promoting the RIMAP (Risk Based Inspection and Maintenance Procedure for European Industries) project.

In those ways, interest in RBM is deep in industry, academia, and government in Japan, and in Europe and the United States, organizational research and development is progressing.

In addition, in October 2003 Japan Society of Maintenology was formed with Professor Miya of Keio University as Chair by users of preservation technology mainly in nuclear power plants. In 2001, the National Institute for Materials Science began a five-year project on "research concerning the development of material risk information platform for safe use of materials." The Japan Science and Technology Agency began its five-year Failure Knowledge Database project in 2001 to gather case studies of failure in various types of plants. The National Institute for Materials Science has been creating data sheets on creep and fatigue for over 30 years, compiling one of the world's best databases.

From the above, we can see that knowledge of the importance of maintenance is now growing in industry, academia, and government, and that Japan's technological potential is sufficiently high in comparison with Europe and the United States.

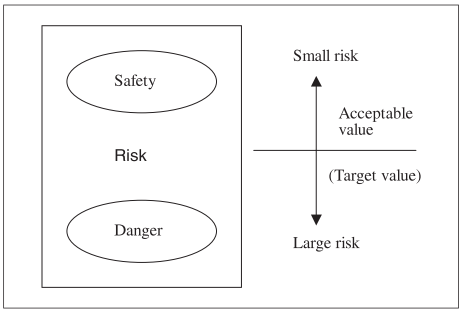
4 Overview of risk based maintenance (RBM)

As shown in Figure 4[7], risk incorporates both safety and danger. When risk is lower, safety is higher; when risk is higher, danger is higher. Until now, absolute safety has been required in Japan, but the line between safety and danger is often obscure. In the concept of risk management, the line between danger and safety is drawn at the level of acceptable risk. People from a variety of fields contribute to the determination of acceptable risk, enabling a broad consensus on danger and safety to be reached. Concretely, risk is expressed as the product of "the probability that failure will occur" and "the amount of consequence that would be caused by the failure."

The RBM method began in Europe and the United States, and some application of it has begun in Japan as well[8]. The method is rational because it indexes risk and uses it to set maintenance priorities, thus reducing unnecessary inspections and prioritizing investment where risk is high. As mentioned in Section 2, existing technology has elements that can determine where failure is likely (probability), but it is also necessary to determine what damage would be caused by failure. With risk as the standard, emphasis is placed on necessary maintenance, enabling highly reliable maintenance at low cost.

Figure 5 shows an example of the RBM process and necessary development areas. The process is as follows.

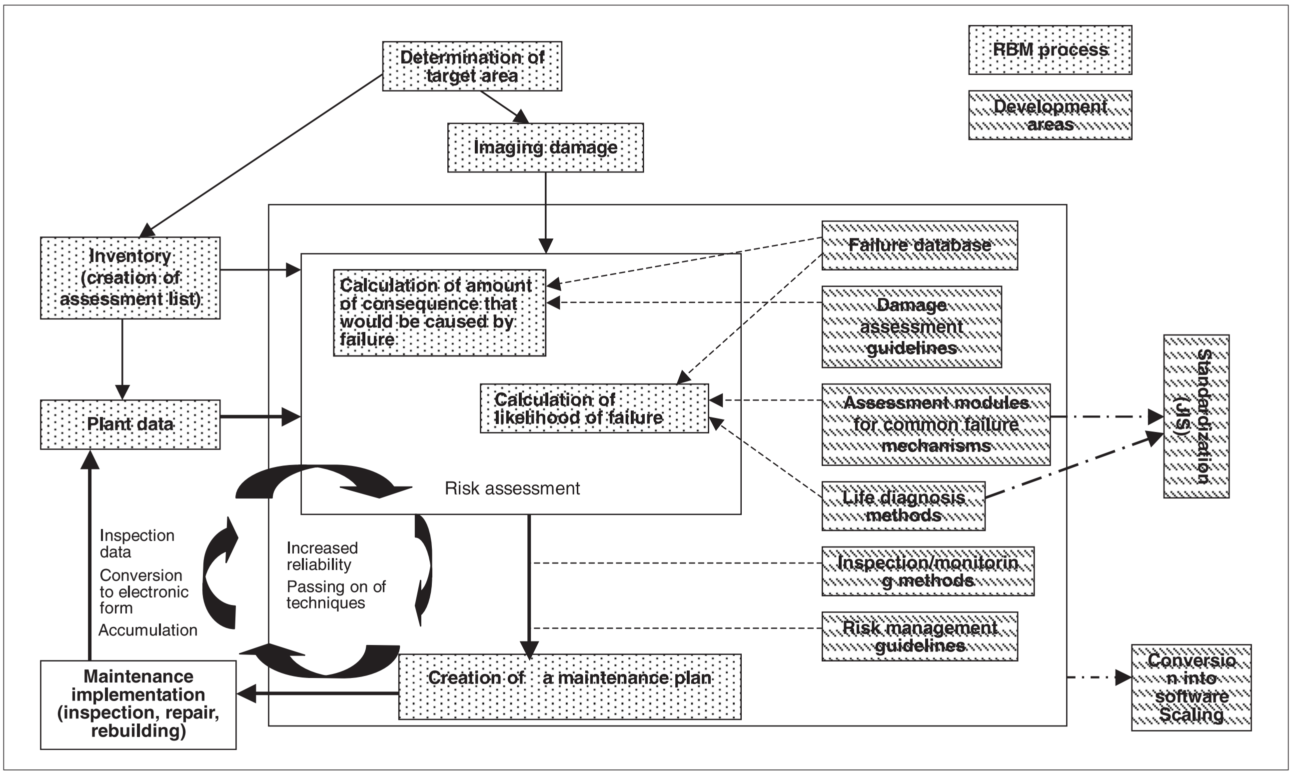
Figure 4 : The concept of "risk"



(1) Preparation

- Determination of target area: determination (by manager) of the extent of RBM application (entire plant, specific equipment, etc.).
- Imaging damage: imaginary of the possible human, economic, and environmental damage that could be caused within the target area.
- Inventory (creation of assessment list): the target area is classified, with the smallest parts to be assessed (assessment units) listed. Failure mechanisms to be concerned with for each part are established.
- Plant data collection and input: data such

Figure 5 : Example of the RBM process and necessary development areas



as design parameters, operating history, and inspection results are collected and processed.

(2) Assessment

- Risk assessment: "the amount of consequence that would be caused by failure" and the "likelihood of failure" are calculated separately, and as shown in Figure 6[9], plotted in a risk matrix. Figure 6 shows a semi-quantitative method, with each property expressed in four levels (it need not be 4×4).

  In addition, if calculation is detailed, likelihood of failure can be expressed as probability and amount of harm as money. Results of the risk ranking are reflected in the inspection categories in the next inspection and in repairs in the maintenance plan, and so on. In this case, four categories of risk levels have been determined.
- Calculation of amount of consequence that would be caused by failure: the amount of human and economic damage that would be caused by failure is calculated. If the process liquid is explosive, toxic, or polluting, detailed analysis with thermal or fluid analysis technology is used to determine the amount that would be released and the extent of its spread and calculate the amount of damage.
- Calculation of likelihood of failure: Probability of failure from past cases, life assessment, effectiveness of inspection, severity of operation, management circumstances, and so on are used to calculate the likelihood of failure within a given time period.

(3) Maintenance planning and implementation

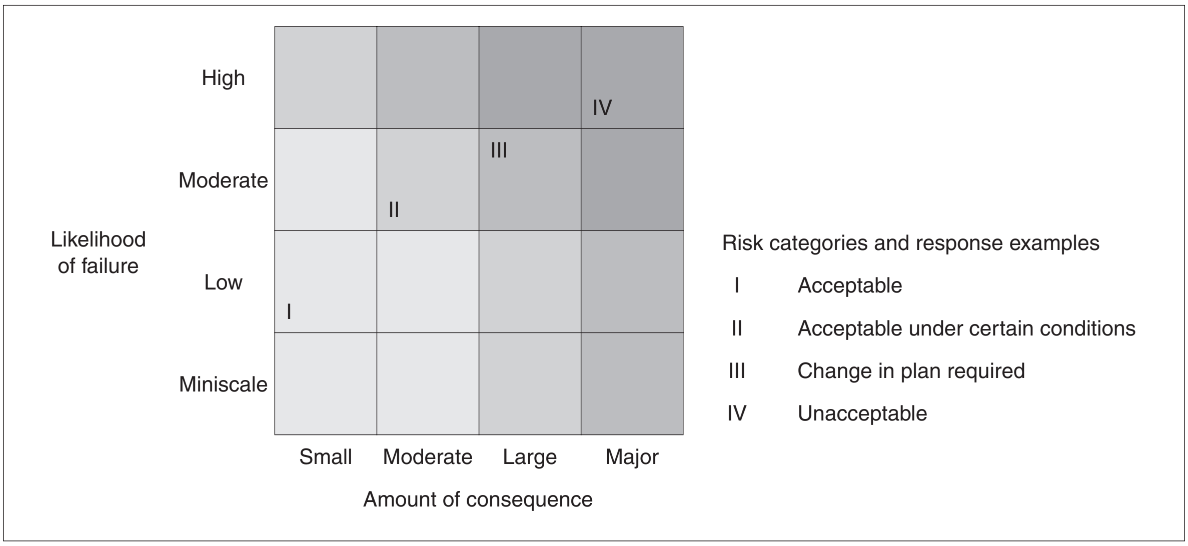
- Creation of a maintenance plan: As a result of the risk assessment, a maintenance plan that includes measures to lower risk in high risk areas is created. Risk-lowering measures may include more effective inspection methods, implementation of monitoring, improved operating conditions, and steps to lessen possible harm.
- Maintenance implementation: Maintenance is implemented in accordance with the plan above.

Data gathered through maintenance is fed back as plant data and reflected in the next round of maintenance. As this is repeated and data is accumulated and processed, reliability improves. Another result is the conversion of the data to electronic form and the passing on of techniques.

The development categories required for the establishment of RBM are as follows:

- Failure database: cases of failure from various plants are collected and sorted. The database is used to calculate consequence and likelihood of failure.
- Damage assessment guidelines: guidelines for the calculation of consequence and likelihood

Figure 6 : Risk ranking matrix and response examples



of failure.

- Assessment modules for common failure mechanisms: methods to assess sensitivity to failure through each fracture mechanism.
- Life diagnosis methods: various life diagnosis methods are sorted and impact on risk is assessed.
- Inspection/monitoring methods: development of inspection/monitoring methods to reduce risk and assessment of their impact.
- Risk management guidelines: guidelines regarding methods to reduce risk.
- Code: assessment modules for common failure mechanisms, life diagnosis methods, and so on are coded for easy general use.
- Standardizing the RBM process and converting it into software: the RBM process is standardized and converted into software for easy general use.

Because risk can be expressed quantitatively (in term of money), the value of investment in maintenance can be calculated and used as information in making management decisions. In financial engineering and other forms of advanced asset management, a quantitative risk value can be utilized as important data. Furthermore, large-scale plants such as power generating stations must share ideas regarding safety with the general public can use acceptable risk standards as a tool to speak objectively to the public. For those reasons as well, risk-based management methods are garnering attention from a wide range of people.

To implement RBM methods as described above, almost all the categories in Section 5 below, "The optimal future of maintenance," are necessary. Progress in RBM research will lead the future of maintenance in the correct direction.

5 The optimal future of maintenance

For Japan, which must maintain and use its vast social and industrial infrastructure with care, the following is necessary.

(1) To more accurately predict failure, life prediction technology should be improved through the application of advanced sensing technology.

(2) To create an environment in which a broad range of people, including the lay public, can discuss the safe operation of structures from a common perspective. It is absolutely necessary that the results of long years of research into understanding of fracture mechanisms and life prediction technology should become common sense.

In concrete terms, the following is proposed.

- To disseminate the idea of risk as the standard for a generally shared perspective on safety.
- To disseminate technologies already established such as life assessment methods by standardizing them and converting them into PC software.

(3) Vitalization of maintenance technology fields.

- Maintenance technology requires a broad range of fields. Primary amongst them are mature fields such as, strength of materials, metals science, thermodynamics, and fluid dynamics. Currently in Japan, research and development and education are insufficient in those fields. Regarding the training of maintenance engineers as well, universities should spotlight research and education in such fields.
- A certification system for maintenance engineers should be established.

(4) Frameworks for responding to globalization (the advancing adoption of imported products) must be developed.

- Information on worldwide materials characteristics, materials standards, cases of failure, and so on should be collected in easy-to-use databases.

6 Conclusion

Based on the above, I propose the following science and technology policies.

(1) Among maintenance technologies, life prediction methods, risk assessment

methods (soft), and maintenance related (failure case studies, materials characteristics, etc.) databases should be highly accessible, and assessment standards must be based on broad consensus. Furthermore, the responsibility of maintaining the majority of social infrastructure belongs to the national government. Therefore, the government should invest research and development funds to develop maintenance technologies. At present, using national government funds to drive research in RBM, which is drawing the joint attention of industry, government, and academia, would be effective. Funds should be invested in academic societies and other public institutions, and committees should be established to develop techniques and standards.

(2) Maintenance integrates engineering fields such as structural materials sciences like materials strength and ferrous materials with thermo-dynamics and fluid mechanics. Those engineering fields are mature, and their attraction as research fields is weak and student interest is also low. Nevertheless, they are vital engineering fields if structures are to be maintained safely.

Taking them from the new perspective of safety, those engineering fields can be seen as a new R&D/academic field including social science fields such as safety science and financial engineering for asset value assessment. In Europe and the United States as well, maintenance is not systematized. It should be organized into an academic discipline, with graduate school majors in maintenance science and maintenance technology research centers that draw a broad range of personnel from Japan and abroad and promote education in the field.

(3) Government and the private sector should work together to prepare maintenance-related standards and to implement the setting and revising of standards in accordance with technical progress. Standards that stimulate the rationalization of maintenance should be welcome during the current trend towards deregulation.

(4) With the number of maintenance engineers decreasing, the quality of those few engineers must be ensured by national government policy that actively encourages maintenance-related academic associations to set qualification standards for maintenance engineers.

The modernization and rationalization of maintenance through the implementation of RBM as described above will also have the following propagation effects, and should be achieved promptly.

- Maintenance costs are expected to tie up corporate management in the future, but the quantification of risk and maintenance costs may become an important tool for management decision making. A new academic field fusing management engineering with maintenance science may open.
- Establishing maintenance techniques will bring about the safe extension of facilities and equipment life, resulting in a significant reduction in industrial waste.
- The establishment and implementation of maintenance techniques will result in their reflection in the design and production of new structures. This may lead to the development of risk-base engineering that will establish optimal designs for structure life[10,11].
- It is projected that when neighboring countries inevitably face the same situation after years from now, Japan can take a leadership role and its maintenance businesses can develop abroad.

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