Data Science Journal, Volume 12, 13 January 2014

CONSTRUCTING ONTOLOGY FOR KNOWLEDGE SHARING OF MATERIALS FAILURE ANALYSIS

Peng Shi*, Jindong Huo, Qingmei Wang

National Center for Materials Service Safety, University of Science and Technology Beijing, Beijing, China
**E-mail:* shipengustb@sina.com

ABSTRACT

Materials failure indicates the fault with materials or components during their performance. To avoid the reoccurrence of similar failures, materials failure analysis is executed to investigate the reasons for the failure and to propose improved strategies. The whole procedure needs sufficient domain knowledge and also produces valuable new knowledge. However, the information about the materials failure analysis is usually retained by the domain expert, and its sharing is technically difficult. This phenomenon may seriously reduce the efficiency and decrease the veracity of the failure analysis. To solve this problem, this paper adopts ontology, a novel technology from the Semantic Web, as a tool for knowledge representation and sharing and describes the construction of the ontology to obtain information concerning the failure analysis, application area, materials, and failure cases. The ontology represented information is machine-understandable and can be easily shared through the Internet. At the same time, failure case intelligent retrieval, advanced statistics, and even automatic reasoning can be accomplished based on ontology represented knowledge. Obviously this can promote the knowledge sharing of materials service safety and improve the efficiency of failure analysis. The case of a nuclear power plant area is presented to show the details and benefits of this method.

Keywords: Knowledge sharing, Materials failure analysis, Ontology

1 INTRODUCTION

Materials service safety has been receiving more and more attention because safety problems can cause large economic losses and decrease public security. To investigate the principles of materials service safety, academic experiments are executed that simulate the behaviors of materials service. However, the use of experimental data only cannot give satisfactory assessment results because of important factors, such as a difficult simulated complex industrial environment and immature accelerating test methods.

Another means available to evaluate materials service safety is materials failure analysis. Materials failure indicates the faults with materials or components during their service. Typical examples of occurred materials failure are called materials failure cases. Failure cases record the realistic service conditions and environments of materials, components, and equipment. Therefore, failure cases are regarded as the firsthand data of materials service safety assessment.

Two factors crucial for a successful failure analysis are sufficient historical failure data and capable domain experts. Historical failure data indicate the occurred failure cases and analysis results. Past failure data can provide authentic references for current failure analysis. To accelerate and share valuable data of failure cases, some materials failure case bases have been designed and developed for the purpose of research, employee training, design improvement, and so on. The Senior Network of the Society of Chemical Engineers Japan has published a failure case base. This case base involves more than three hundred typical failure cases mainly in petroleum refinery and chemical plants, which were collected and analyzed by materials and maintenance specialists. Li, Qu, Luo, and Li (2004) developed a case base focusing on the corrosion failure of a buried pipeline. A bridge failure database was established by George Lee, O'Conner, Qi, and Wang (2008) for better designing and maintaining of bridges. There are also web sites for failure case sharing through the Internet. The Japanese failure case knowledge database shares hundreds of failure cases in PDF documents (http://www.sozogaku.com/fkd/en/index.html). WANG, WU, WANG, WANG, and LIU (2009) established a web-based case base, focusing on materials corrosion failure cases. Another web-based case base for sharing environmental corrosion failure was designed and developed by CHEN, WU, and ZHU (2010). Shi, Jin, and Shen (2010) established a failure case base for materials service safety assessment. With these failure case base systems, users can obtain failure case data manually.

However, the use of failure data alone in a failure analysis may not lead to a correct conclusion. Domain experts must perform the analysis procedure because they possess the required knowledge, in particular application area knowledge, failure mechanism knowledge, and materials knowledge. To improve the efficiency and veracity of failure analysis, it is necessary to share the knowledge of failure analysis with other researchers and engineers.

In the past decades, many researchers dedicated themselves to the methods of knowledge representation and sharing. With the advent of the Internet and Semantic Web (Berners-Lee, Hendler, & Lassila, 2001), ontology has been adopted as the most popular tool for knowledge representation and sharing. Ontology is a concept that originated in the field of philosophy. It indicates the specification of a conceptualization (Gruber, 1995). Ontology has been successfully utilized in materials science. For the integration of varied format materials data from rich resources, Ashino (2010) proposed an infrastructure for exchanging materials information and knowledge. It adopted ontology and OWL as tools to realize materials data exchange. Cheung, Drennan, and Hunter (2008) gave an extensible ontology, called MatOnto, to represent structured knowledge about materials, their structure and properties, and the processing steps involved in their composition and engineering. To enrich the semantic information of MatML, which is often used to describe materials data in XML format, Zhang, Hu, and Li (2009) proposed a method to transform MatML-based materials data into OWL format ontology.

The review above illustrates that current materials ontologies mainly focus on basic knowledge of materials science. They are only utilized for data exchange and knowledge representation. For further application, such as materials failure analysis, new ontology should be constructed. This paper describes the construction of an ontology for materials failure analysis that can improve the efficiency and validity of case analysis. The remainder of this paper is arranged as follows. Section 2 describes the related concept of materials failure and the traditional procedure of failure analysis. The ontology based representation of domain knowledge and failure case is shown in Section 3. Section 4 gives the main benefits of ontology based knowledge sharing. Finally, Section 5 gives the conclusion and future work.

2 MATERIALS FAILURE ANALYSIS

2.1 Failure data collection

In general, past experience is a good reference to guide current decision making. Therefore, materials failure analysis is very useful for failure prevention and system maintenance. For effective failure analysis, the data of a failure and possible following accidents should be collected as often as possible. It should include, at the very least, information about the failure object, service environment, service period, failure result, accident description, accident treatment, site observation, and lab analysis.

Information about the failure object includes the material's composition, geometric shape, and its location within the system. Most engineering materials are made into components, such as pipes, boards, and girders. Different components may perform differently although their materials are the same. The movement of the failure object should also be recorded.

The service environment indicates the chemical and mechanical environments that surround the object. The chemical environment includes the mediums inside and outside the service object. For example, benthonic petroleum pipes are used to transport petroleum from sea to shore. Here petroleum is the medium inside the pipe and seawater is the medium outside the pipe. Both inside and outside mediums can cause pipe corrosion. The mechanical environment is the stress added to the service object. For instance, the benthonic petroleum pipes are compressed by hydraulic pressure inside and battered by waves on the outside. It should be noticed that the service environment changes during the service period.

The service period runs from the beginning of service to the time when the failure occurs. Usually service objects used over a long time period have greater failure possibilities than those used for shorter periods under the same or similar conditions. This is important to note during the analysis and in the prediction of the safety service lifetime, according to the past case analysis results.

Failure result gives the direct consequence of a failure. Equipment destruction, people injured, economic loss, and environment influence should be emphatically described.

Accident description is a document in which the whole accident is specified in detail. It describes the beginning, proceeding, and consequences of the occurred failure, in text, photos, diagrams, videos, and any other useful formats.

Accident treatment indicates the steps taken by operators after a failure to reduce the effects of the failure and avoid further accidents. The effectiveness of the treatment should be recorded. The treatment and its effects are very useful for future similar accident influence control.

Site observation consists of the realistic situation of the failure. Its most important content is the photos of the site. Other related phenomena should also be recorded objectively by experienced observers. Domain experts should study the contents manually to get clues from the failure and decide the need for further lab analysis.

Lab analysis consists of necessary lab experiments to obtain detailed information, such as the chemical composition of the corrosion product, the crack length, and the mechanical performance. When the lab analysis is finished, a domain expert can draw conclusions about the tested materials as well as direct results. The failure analysis must be executed by domain experts who use all the collected data of the failure.

2.2 Failure analysis

Failure analysis is the common name for the procedure used to discover the causes of a failure. Usually failure analysis is executed by experienced domain experts. First, they investigate the data from the failure site or directly observe the site. From the site situation, the reasons for the failure can, in some cases, be confirmed. In other cases, lab analysis is recommended to get further information through testing and experiments. Based on site information and results from the lab analysis, domain experts analyze and reason according to their knowledge and experience of materials service. In conclusion, a case analysis result is presented that includes reasons for the failure and strategies for improvement.

There are two key steps in failure analysis: the discovery of the key materials and factors influencing materials service behaviors and the reasoning that leads to conclusions based on personal knowledge and experience. Sufficient knowledge of the domain is needed to perform these two steps.

3 ONTOLOGY CONSTRUCTION

3.1 Ontology, RDF, and OWL

Ontology is now widely used to represent domain knowledge to support intelligent applications. Ontology often consists of a set of classes (concepts), relations, functions, axioms, and instances.

With the development of the Semantic Web, the standards of ontology have been developed and published. Resource Description Framework (RDF) and Web Ontology Language (OWL) are two standard languages that describe ontology as recommended by the World Wide Web Consortium (W3C) (W3C standards, available from http://w3.org). RDF is used to identify the data objects, and OWL is used to represent implicit relationships through explicit means. In this paper, we adopt the OWL language to describe ontology and represent knowledge.

3.2 Application area knowledge

Application area knowledge indicates the background knowledge of the area in which the failure occurred, such as an industrial system or civil engineering system. In general, one application area has normalized, explicit, and fixed process and structure. There are different relationships among components and equipment in a system. These relationships can be explicitly represented by ontology. From the aspect of ontology, materials, components, and equipment can be regarded as objects. The relationships among them can be represented by extended properties of ontology.

In this paper, a nuclear power plant is taken as an example of application area. A nuclear power plant utilizes a nuclear reactor to produce electric power. The safety of nuclear power plants always attracts much social attention because a failure may cause serious disasters such as nuclear pollution. For example, in 2011 the failure caused by an earthquake at the Fukushima nuclear power plant has influenced the Japanese people’s health as well as the global environment. Therefore, failures in a nuclear power plant should be analyzed carefully to avoid future failures and accidents.

The main procedure to transform the knowledge of an application area into ontology is shown as follows. First, we transform the application area diagram into an object relationship diagram. Then, a domain expert checks and normalizes the object relationship diagram. Finally, ontology is constructed according to the normalized object relationship diagram. At the same time, corresponding OWL sentences are created from ontology by software tools, such as Protégé (http://protege.stanford.edu/).

Figure 1. (a) shows a simplified system diagram of a nuclear power plant (http://www.world-nuclear.org/). There are two main parts and two connected components. The containment structure generates steam and transports it into the turbine generator through a steam line. The turbine generator produces power from the steam energy. Cooling water decreases the temperature of the used steam. The cooled steam is transported back into the steam generator through a pump and reheated by the steam generator. Figure 1. (b) shows the relationship diagram of the nuclear power plant established from Figure 1. (a). After the definition of objects and new properties, domain ontology can be built and stored as an OWL file. The segment of the created OWL file of a nuclear power plant area is shown in Appendix A.

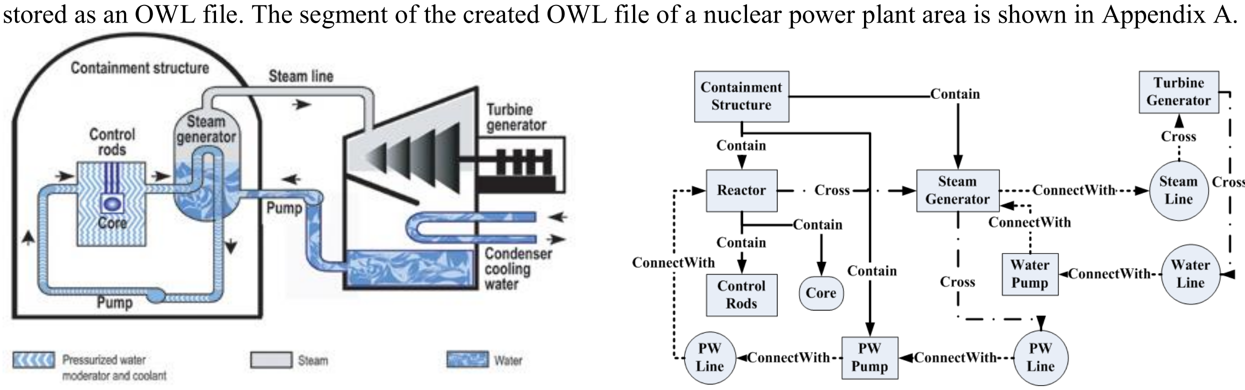

Figure 1. (a) Structure diagram of a nuclear power plant **(b)** Simplified relationships among the components of a nuclear power plant

3.3 Failure mechanism knowledge

Along with information about the application area, information about the failure mechanism is also important for failure analysis. The failure mechanism indicates the primary principle, mode, and consequence of one kind of failure. The failure mechanism of the same material may be varied in different service environments and application areas.

Researchers and engineers have investigated the phenomena and mechanism of materials failure for centuries. Dasgupta and Pecht (1991) have summarized the knowledge of materials failure in some areas. Failure knowledge mainly includes the names of the materials and components, their failure mechanism and mode, and the factors and methods for life evaluation. Unfortunately, this kind of knowledge is possessed by the domain expert in a personalized and hard-to-share format. Therefore, we must obtain it from domain experts and represent it with an easy-to-share format, such as ontology and OWL files.

Using the failure knowledge of a nuclear power plant as an example, we gathered information from references and domain experts. All the items of the failure knowledge are represented in OWL format. A component is defined as a *"Class"*. A different component is indicated as a "subClass" of the class *Component*. The failure mechanism and mode are defined as the *"ObjectProperty"* of the components. The failure mode and mechanism are indicated as a *"Class"*, with its subclasses (different kinds of modes and mechanisms) and properties. A segment of a failure knowledge OWL file is shown in Appendix B.

3.4 Failure case representation

In order for failure cases to be shared over a wide area, they must be represented in an easy-to-share format. In this paper, we represent a failure case for data sharing through the Internet in OWL format. A failure case consists of the failure object, service environment, service period, and other information, as shown in Section 2.1.

We take a failure case of nuclear power plant from (http://www.sozogaku.com/fkd/en/index.html) as an example. The simplified text description of the failure case is as follows:

At 13:50, on February 9th, 1991, a heat transfer tube (SG tube) in a steam generator of the No.2 pressurized water reactor at the Mihama nuclear power station of the Kansai Electric Power Company broke off during a rated output operation. As a result, about 55 tons of primary cooling water leaked out from the SG tube into the secondary cooling loop, and the reactor was scrammed by operation of the ECCS (Emergency Core Cooling System). The failure of the SG tube was caused by fretting fatigue resulting from contact of the SG tube with the supporting plate for the SG tubes, because the AVB, which functions to prevent flow-induced vibration, was not inserted deep enough onto the SG tubes in the steam generator. At 13:40, an alarm of a condenser air off take system went off during a rated output operation, warning that the coolant water level in the steam generator was decreasing. At 13:50, an automatic emergency shutdown of the reactor was triggered by the signal of decreasing pressure in the pressurizer. After seven seconds, the ECCS was automatically operated, and coolant water was flooded into the reactor by a high pressure injection pump. However, one main steam isolation valve and one pressurizer relief valve could not be operated by remote control. Therefore, the valve operation was carried out manually. After the accident, investigation of the steam generator was carried out using a fiber scope and some other inspection instruments. The scale of the accident was ranked 'level 3' on the international nuclear events scale (INES).

This case can be transformed into an individual in OWL format. A segment of the Mihama failure is shown in Appendix C. By use of the OWL format, application area knowledge, failure knowledge, and materials failure cases can be easily represented and shared.

4 BENEFITS FROM ONTOLOGY

After the domain ontology is constructed, several benefits for materials failure analysis can be realized. One is the support of the intelligent retrieval of related cases from the case base. The second is the acquisition of knowledge based data statistics, which show more useful information than traditional keyword based statistics results. Another is the realization of automatic reasoning for failure analysis based on the reasoning mechanism provided by the ontology.

4.1 Related cases retrieval

When experts execute a failure case analysis, past materials failure cases are important references. Therefore, related cases (especially similar cases) should be able to be obtained conveniently and precisely. The traditional case base stores failure cases in a 2-dimensional table. The retrieval is programmed on the basis of keywords matching. Unfortunately, the keyword-based failure case retrieval often returns bad results because the knowledge of users is not consistent with the keywords used in the case base system. With the help of ontology of the background knowledge, the retrieval of failure cases is based on the semantic level and thus can avoid the shortcomings of keywords based retrieval.

When a new case is proposed for analysis, the user first normalizes the case. That is, the new case is represented in OWL format with the standard framework as well. According to the situation, users can establish query statements based on the characteristics of the new case. The query condition may involve the material, shape, stress situation, service environment, and so on. Of course the query conditions can be joined by logic relationships, such as AND, OR, NOT, and their flexible combinations.

For example, a new case of an underground petroleum pipe is proposed to be analyzed. According to the user's experiences, the chemical and stress service environment are important factors for the corrosion of this kind of pipe. Thus the user establishes a combination query condition with inner liquid type and outer stress situation. Using SPARQL Language recommended by W3C (http://w3.org) query results can be easily obtained from OWL files. The core query statements in SPARQL are written as follows:

```
SELECT ?InnerMedium ?Stress ?Result ?ServicePeriod FROM <PipeCase.rdf> WHERE { ?PetroleumPipe InnerMedium “OIL-1”. FILTER Stress > 9kN}
```

The segment of retrieval result is shown as following:

```
<PetroleumPipe rdf:ID="Pipe023">
  <InnerMedium ref:resource="OIL-1"/>
  <Stress rdf:resource="10kN"/>
  <Result rdf:resource="ElasticDeformation"/>
  <ServiecPeriod rdf:resource="12years"/>
</PetroleumPipe>
<PetroleumPipe rdf:ID="Pipe156">
  <InnerMedium ref:resource="OIL-1"/>
  <Stress rdf:resource="22kN"/>
  <Result rdf:resource="Cracked"/>
  <ServiecPeriod rdf:resource="5years"/>
</PetroleumPipe>
```

In the OWL file above, OIL-1 is the name of one kind of oil whose chemical composition is recorded in another table with the percentages of all its elements. From the retrieval results, the user finds that there are two cases similar to the case to be analyzed. The analysis results of the two cases are also retrieved from the failure case base. One case shows that “Pipe023” with 10kN stress elastically deformed after 12 years. The other case describes that the pipe with 22kN stress cracked after 5 years' service. Therefore a simple conclusion can be drawn - the pipe may be used safely for only 5 years under 22kN stress.

4.2 Intelligent failure case statistics

Because the keyword is the basis for executing case statistics in current systems, the exact statistics depend on consistent keywords in different data resources. Unfortunately, different data resources may adopt various data dictionaries. In this case, domain knowledge should be introduced to improve the case data statistics because it contains the semantics information of a domain. The semantics information includes the synonyms, near-synonyms, antonyms, and the relationship between the elements in one domain, based on what better case statistics results can be produced.

When making ontology based data statistics, the data of every case is compared with the ontology of the domain knowledge. Through the match between single case and domain knowledge, all failure cases in the same domain will be classified into the correct category according to the domain knowledge. The statistical data of all failure cases can be attained through general methods.

Failure case statistics can be generated from different aspects to assist with the failure analysis, for example, from materials, components, and failure mode. The statistical data based on materials can show which material easily failed in which kinds of environments, and discovering the weaker part of a component will be clearly based on statistical data from many failure components. The frequency of failure mode describes the different means of destruction in a certain service environment. Other aspects can also be regarded as important factors in making data statistics according to application demands. Furthermore, an improved strategy can be made based on the statistical data to enhance the service safety from several aspects.

From the statistical results of failure cases, domain knowledge can also be enriched. For example, steam line failures caused by corrosion occupy about 30% of total steam line failures. This kind of statistical data is very useful in improving the design and maintenance of easily failed components so that their service lives can be prolonged effectively.

4.3 Automatic reasoning in failure analysis

Since ontology provides the function of reasoning, automatic reasoning is possible based on ontology. With sufficient ontology representing domain knowledge and reasoning rules, failure analysis may be executed automatically or semi-automatically.

The main procedures of automatic failure analysis are as follows. First, the system transforms the received new case into OWL format. The new case represented in OWL is easily decomposed by XML file parsing. The system identifies several service conditions from the parsed results. These conditions are converted into corresponding query statements. Then a set of query conditions are executed according to the query statements. The query statements are combined and joined by different logical relationships. The structure of different combinations is adopted according to the case analysis rules. Based on the combined retrieval results, a reasoning procedure is executed automatically by the system with the support of reasoning rules repository. The repository stores OWL described rules for failure case reasoning. The establishment and utilization of reasoning rule repository and automatic reasoning will be investigated in the future.

4.4 Safety evaluation and life prediction

Based on OWL represented historical failure cases and domain knowledge, safety evaluation and life prediction can be executed. When a case, usually a servicing case, is proposed for evaluation, the first task is to retrieve similar failure cases in the same application area. If there are cases with the same service environment as that of the case, only the service period of these cases should be investigated. If the service period of a past case is larger than that of new case, the situation of the new case is still safe, and the remaining safety lifetime of the new case is less than or equal to the past case's service period minus the new case's service period. For example, a new design case of an underground petroleum pipe to transport oil from place A to B is evaluated to determine whether this kind of pipe can safely serve for 10 years. The retrieval results from the case base show that another petroleum pipe with the same material and shape had served safely for 12 years from place A to place C. Place B and place C have a similar natural climate and geological environment. Thus a direct conclusion can be drawn that the pipe in the new case can satisfy the demand and can even serve for 12 years.

If there are no similar cases in the case base, the new case has no related cases to be referred to. The evaluation must be submitted to experienced domain experts. It is the domain expert's responsibility to analyze this case manually. The analysis results and the whole procedure are then recorded as a virtual evaluation case. When similar cases are analyzed in the future, the system can give conclusions according to these virtual cases.

5 CONCLUSION AND FUTURE WORK

Failure analysis is important for the improvement of designing, producing, servicing, and maintaining materials. This paper proposes an ontology based method for materials failure analysis knowledge sharing. With this shared knowledge, intelligent failure case retrieval, advanced statistics, and automatic reasoning can be realized. Our method can obviously improve the efficiency and veracity of materials failure analysis and supply better training for domain researchers and engineers.

Future work focuses on the improvement of the logical description of reasoning rules so that automatic materials failure analysis can be accomplished. Another work for the future is to collect sufficient materials failure cases and knowledge to satisfy the demand of knowledge sharing in more application areas.

6 ACKNOWLEDGMENTS

This work is financially supported by the “National Program on Key Basic Research Project (973 Program No.2013CB329606)”, the “National Natural Science Foundation of China (51101016)”, and the “Fundamental Research Funds for the Central Universities (No.FRF-TP-12-162A)”.

7 REFERENCES

Ashino, T. (2010) Materials Ontology: An Infrastructure for Exchanging Materials Information and Knowledge. *Data Science Journal 9*, pp 54-61.

Berners-Lee, T., Hendler, J., & Lassila, O. (2001)The Semantic Web. *Scientific American 284*(5), pp 29-37.

CHEN, J., WU, M., & ZHU, B. T. (2010) Web-based Environmental Corrosion Failure Case System. *Contemporary Chemical Industry 39*(3), pp 336-344.

Cheung, K., Drennan, J., & Hunter, J. (2008) Towards an Ontology for Data-driven Discovery of New Materials. *Proc. Semantic Scientific Knowledge Integration AAAI/SSS Workshop,* Stanford, USA, pp 26-28.

Dasgupta, A. & Pecht, M.(1991) Material Failure Mechanisms and Damage Models. *IEEE Transactions on Reliability 40*(5), pp 531–536.

Gruber, T. R. (1995) Towards Principles for the Design of Ontologies Used for Knowledge Sharing. *International Journal of Human-Computer Studies 43*, pp 907-928.

Lee, G., O'Connor, J., Qi, J. C., &. Wang, Z. Q. (2008) Development of a Bridge Failure Database. *Fourth US-Taiwan Bridge Engineering Workshop*.

Li, Y., Qu, Z., Luo, D., Li, X. (2004) Design and Research of Case Base for the Corrosion Failure of Buried Pipelines. *Corrosion and Protection 25*(12), pp 541-543.

Shi, P., Jin, Y., & Shen, B. (2012) Failure Case Base for Materials Safety Assessment. *Proceedings of The 3rd Asian Materials Data Symposium*, Japan, pp 123-127.

WANG, Y. B., WU M., WANG, W. Q., WANG, D. D., & LIU, S. S. (2009) Design and Development of Case Base Based on Web for Corrosion Failure of Materials. *Corrosion and Protection 30* (1), pp 72-74.

Zhang, X., Hu, C., & Li, H. (2009) Semantic Query on Materials Data Based on Mapping MatML to an OWL Ontology. *Data Science Journal 8,* pp. 1-17.

8 APPENDICES: OWL SEGMENT OF NUCLEAR POWER PLANT ONTOLOGY

A Application area knowledge


```
<owl:Class rdf:about="http://www.semanticweb.org/dell/ontologies/2013/7/NuclearPowerPlant#Component" />
<owl:Class rdf:about="http://www.semanticweb.org/dell/ontologies/2013/7/NuclearPowerPlant#Condenser">
   <rdfs:subClassOf
rdf:resource="http://www.semanticweb.org/dell/ontologies/2013/7/NuclearPowerPlant#Component" />
</owl:Class>
<owl:Class rdf:about="http://www.semanticweb.org/dell/ontologies/2013/7/NuclearPowerPlant#Containment">
   <rdfs:subClassOf
rdf:resource="http://www.semanticweb.org/dell/ontologies/2013/7/NuclearPowerPlant#Component" />
</owl:Class>
<owl:Class rdf:about="http://www.semanticweb.org/dell/ontologies/2013/7/NuclearPowerPlant#ControlRods">
   <rdfs:subClassOf
rdf:resource="http://www.semanticweb.org/dell/ontologies/2013/7/NuclearPowerPlant#Component" />
</owl:Class>
<owl:Class rdf:about="http://www.semanticweb.org/dell/ontologies/2013/7/NuclearPowerPlant#CoolingWater">
   <rdfs:subClassOf rdf:resource="http://www.semanticweb.org/dell/ontologies/2013/7/NuclearPowerPlant#Water"
/>
</owl:Class>
```

```
<owl:ObjectProperty
rdf:about="http://www.semanticweb.org/dell/ontologies/2013/7/NuclearPowerPlant#ConnectWith">
   <rdfs:comment rdf:datatype="http://www.w3.org/2001/XMLSchema#string">To describe which component is
connected with the object</rdfs:comment>
   <rdfs:domain
rdf:resource="http://www.semanticweb.org/dell/ontologies/2013/7/NuclearPowerPlant#Component" />
   <rdfs:range rdf:resource="http://www.semanticweb.org/dell/ontologies/2013/7/NuclearPowerPlant#Component"
/>
</owl:ObjectProperty>
<owl:ObjectProperty
rdf:about="http://www.semanticweb.org/dell/ontologies/2013/7/NuclearPowerPlant#BackConnectWith">
   <rdfs:subPropertyOf
rdf:resource="http://www.semanticweb.org/dell/ontologies/2013/7/NuclearPowerPlant#ConnectWith" />
</owl:ObjectProperty>
<owl:ObjectProperty
rdf:about="http://www.semanticweb.org/dell/ontologies/2013/7/NuclearPowerPlant#ForeConnectWith">
   <rdfs:subPropertyOf
rdf:resource="http://www.semanticweb.org/dell/ontologies/2013/7/NuclearPowerPlant#ConnectWith" />
</owl:ObjectProperty>
```

B Failure knowledge

```
<Class rdf:about="http://www.semanticweb.org/dell/ontologies/2013/5/MSS#FailureMechanism"></Class>
<Class rdf:about="http://www.semanticweb.org/dell/ontologies/2013/5/MSS#Corrosion">
   <rdfs:subClassOf rdf:resource="http://www.semanticweb.org/dell/ontologies/2013/5/MSS#FailureMechanism" />
</Class>
<Class rdf:about="http://www.semanticweb.org/dell/ontologies/2013/5/MSS#Erosion">
   <rdfs:subClassOf rdf:resource="http://www.semanticweb.org/dell/ontologies/2013/5/MSS#FailureMechanism" />
</Class>
<Class rdf:about="http://www.semanticweb.org/dell/ontologies/2013/5/MSS#Creep">
   <rdfs:subClassOf rdf:resource="http://www.semanticweb.org/dell/ontologies/2013/5/MSS#FailureMechanism" />
</Class>
<Class rdf:about="http://www.semanticweb.org/dell/ontologies/2013/5/MSS#FailureMode"></Class>
<Class rdf:about="http://www.semanticweb.org/dell/ontologies/2013/5/MSS#Crack">
   <rdfs:subClassOf rdf:resource="http://www.semanticweb.org/dell/ontologies/2013/5/MSS#FailureMode" />
</Class>
<Class rdf:about="http://www.semanticweb.org/dell/ontologies/2013/5/MSS#Deformation">
   <rdfs:subClassOf rdf:resource="http://www.semanticweb.org/dell/ontologies/2013/5/MSS#FailureMode" />
</Class>
<Class rdf:about="http://www.semanticweb.org/dell/ontologies/2013/5/MSS#Exfoliation">
   <rdfs:subClassOf rdf:resource="http://www.semanticweb.org/dell/ontologies/2013/5/MSS#FailureMode" />
</Class>
```

C Failure cases

```
<NamedIndividual rdf:about="http://www.semanticweb.org/dell/ontologies/2013/5/MSS#MihamaNPP1991">
   <rdf:type rdf:resource="http://www.semanticweb.org/dell/ontologies/2013/5/MSS#FailureCase" />
   <MSS:CaseName rdf:datatype="http://www.w3.org/2001/XMLSchema#string">Mihama NPP Economizer
Failure</MSS:CaseName>
   <MSS:OccurredTime rdf:datatype="http://www.w3.org/2001/XMLSchema#dateTime">1991-2-
9:13:50</MSS:OccurredTime>
   <MSS:ServicingTime
rdf:datatype="http://www.w3.org/2001/XMLSchema#float">43050.0</MSS:ServicingTime>
```

<MSS:AccidentDescription rdf:datatype="http://www.w3.org/2001/XMLSchema#string">A heat transfer tube broke off during a rated output operation. About 55 tons of primary cooling water leaked out from the SG tube into the secondary cooling loop, and the reactor was scrammed by operation of the ECCS.</MSS:AccidentDescription>
<MSS:AccidentTreatment rdf:datatype="http://www.w3.org/2001/XMLSchema#string">The valve operation was carried out manually</MSS:AccidentTreatment>
<MSS:FailureComponent rdf:resource="http://www.semanticweb.org/dell/ontologies/2013/5/MSS#SGTube001" />
...
</NamedIndividual>

(Article history: Received 5 September 2013, Accepted 5 October 2013, Available online 7 January 2014)