CODE CASES OF BASKET MATERIAL FOR SPENT FUEL TRANSPORT/STORAGE PACKAGINGS IN THE JAPAN SOCIETY OF MECHANICAL ENGINEERS

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ABSTRACT

The Japan Society of Mechanical Engineers (JSME) established the Rules on Transport/Storage Packagings for Spent Fuel as a part of Codes for Construction of Spent Nuclear Fuel Storage Facilities in 2001, and revised in 2007. The revised Rules provide a material and design code for baskets made of aluminum alloy or borated aluminum alloy. Further, the Rule includes guidelines for the application of aluminum alloy and borated aluminum alloy as a new basket material for the spent fuel transport/storage packagings.

In accordance with the guidelines, proposals of code cases for new basket materials, including 4 types of aluminum alloys and one type of borated stainless steel, were submitted to JSME in late 2007. In January 2008 the Subgroup on Spent Fuel Storage Facilities within the Subcommittee on Nuclear Power in the Power Generation Code Committee of the JSME established the Working Group on Packaging Material Evaluation with experts from universities, research organizations, material manufacturers and utilities to entrust the assessment of these applications. The Working Group met 8 times in a half year to investigate and discuss intensely the applications, and reported to the Subgroup that applied materials were complying with the guidelines in July. For aluminum alloys each set of allowable stress has been set forth with consideration to time and temperature effects such as creep or averaging. The code cases were approved by Subgroup in the end of July, by the Subcommittee in August, and approved for public comments by the Code Committee in December 2008. With no public comment the code cases were finally approved by the Code Committee in March 2009, and published.

These materials are used in basket designs for transport/storage packagings for the Mutsu Recycle Fuel Storage Facility, the first away-from-reactor interim spent fuel storage facility scheduled to be put into operation in 2012.

In the presentation, outline of the materials and major discussions on them within the JSME Committees will be introduced.

INTRODUCTION

"Mutsu Recyclable Fuel Storage Facility", which is Japan's first spent fuel interim storage facility away from reactor, is scheduled to be commissioned in 2012, and its licensing procedure is now in the final stage. The facility will store hundreds of spent fuel transport/storage packages (or, Dual Purpose Dry Metal Casks – DPDMCs).

Regulatory approach toward the licensing of DPDMCs in Japan is known as a "holistic approach", which takes into consideration the interface issues arising between storage and transport and conducts safety analysis in a more holistic manner. The approach considers following interface issues:

- Post storage transport safety depends on the safety during storage,
- Storage safety significantly depends on the safe transport from NPP to the storage facility, and
- Safety analysis for storage depends on the transportability of casks during storage.

As a result storage operators required to maintain the valid transport certificate throughout the storage period.

Early before the above regulatory approach has been revealed, the Atomic Energy Society of Japan (AESJ) established the "Standard for Safety Design and Inspection of Metal Cask for Spent Fuel Storage Facilities" in 2002, then revised in 2004, 2008 and 2010. This standard provides the design requirements to maintain basic safety functions, i.e. containment, heat removal, shielding and criticality prevention, and the structural integrity of DPDMC itself and of spent fuel cladding during transport and storage. Inspection methods and criteria to ensure the basic safety functions and structural integrity over every stage of operations involving DPDMCs, such as in fabrication, pre-shipment at NPP, receiving at storage facility, during storage (in-service) and pre-shipment after storage, are prescribed as well [1].

In parallel the Japan Society of Mechanical Engineers (JSME) established the "Structural Design and Construction Rules on Transport/Storage packagings" in 2001, and revised in 2007. The rules consist of requirements for materials, structural design, construction and inspection of DPDMC components. Three essential components of DPDMC, which are containment vessels, baskets and trunnions, are covered by the rules [1]. In the revision of the rules, three remarkable additions as below were made:

- Requirements for the material of aluminum alloy for basket,
- Requirements for the design of aluminum alloy for basket, and
- Guidelines for the application of aluminum alloy as a new material for the spent fuel transport/storage packaging basket.

These requirements and guidelines consider basket structural integrity during not only the long-term storage but also the transport after the storage [2].

DPDMC designs to satisfy the above voluntary standard by AESJ and rules by JSME can fulfill the holistic approach set forth by the Japanese regulators. The Nuclear and Industrial Safety Agency (NISA) of the Ministry of Economy, Trade and Industry (METI), who is the competent authority for spent fuel transport and storage in Japan, endorsed the JSME rules in March 2009, and will endorse the AESJ standard by the end of 2010.

REQUIREMENTS AND GUIDELINES IN JSME STRUCTURAL DESIGN AND CONSTRUCTION RULES ON DPDMCS

Some designs of DPDMC employ aluminum alloy or borated aluminum alloy (hereinafter referred as "aluminum alloys") as basket material to enjoy merits of better integrity of spent fuel during storage and lager storage capacity per DPDMC, due to better heat conduction property and smaller

specific gravity of aluminum alloys. In the revision of the JSME Structural Design and Construction Rules on Transport/Storage Packagings for Spent Nuclear Fuel in 2007, requirements for the material of aluminum alloy for basket and for the design of aluminum alloy for basket, and guidelines for the application of aluminum alloy as a new material for the spent fuel transport/storage packaging basket design were incorporated.
Design requirements, which basically follow the design rules on the support structures under elevated temperatures, include the followings with consideration of structural integrity of aluminum ally baskets during long-term storage and transport after storage:

- Allowable stress limit values, such as the tensile strength S, the design stress intensity Sm, the design yield stress Sy and the design tensile stress Su, shall be set under the method specified in the “Guidelines for the application of aluminum alloy as a new material for the spent fuel transport/storage packaging basket”,
- Allowable tensile strength values S are employed as a basis for stress intensity limit for the long term loadings, and
- Creep strains are limited not to exceed 0.2 % for membrane strain and 0.4 % for membrane and bending strain.

The first requirement was set forth to take into account the material strength reduction during long-term storage. The second requirement was to control generated stress during storage well below the limit set with consideration of creep strength. The third requirement was set firstly to prevent creep damage during storage, and secondly to avoid effects on the yield and tensile strength against short term loadings such as the drop of DPDMC during the transport after the storage.

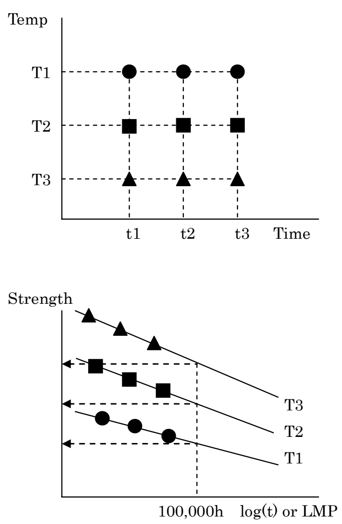
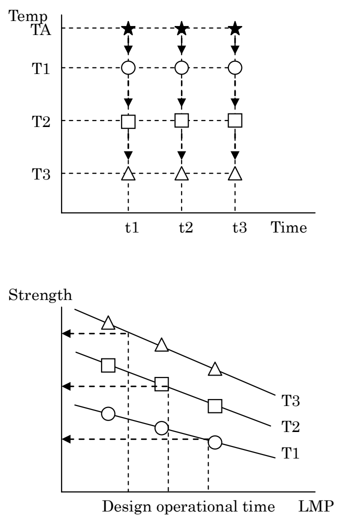
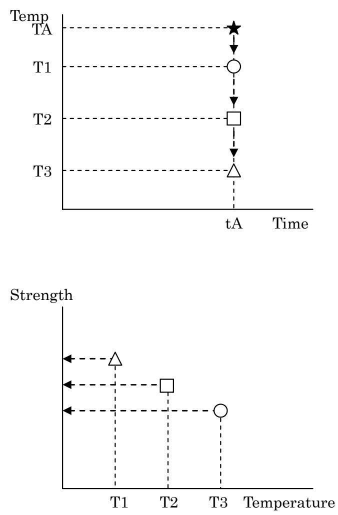
The Guidelines recommend to include the following information in a code case application to JSME for new material to be registered as the basket material of DPDMC.

- Material specification,
- Mechanical properties,
- Creep characteristics and aging characteristics, when applicable,
- Allowable stress values for design, and
- Other explanatory information on manufacturing, testing, data acquisition/processing, etc.

A unique feature of the guidelines is that methods for material strength data acquisition and processing are provided in order to take material strength reduction in heat treated alloys due to overaging during long-term storage into account to set allowable stresses for the material. The outline of the methods is illustrated in Table 1. Tensile tests of alloys should be conducted in consideration with heat treatment temperature (aging) of initial alloy, and predicted temperature history during long-term storage (overaging). The consideration of predicted temperature history of the basket material means that allowable stress values to be set would be dependent to specific DPDMC design.

No aluminum alloy was nominated in the list of registered material for basket in the JSME Rules on Transport/Storage Packagings for Spent Nuclear Fuel 2007 Revision, but the guidelines enabled designers and material suppliers to apply code cases of their new material to be registered to the JSME Rules.

Table 1. Data acquisition and processing method for aged aluminum alloy

	Method 1	**Method 2**	**Method 3**
	Aging duration is taken as a parameter (1)	Aging duration is taken as a parameter (2)	Use specimen aged equivalent to design life
Relation between aging temperature and test temperature	Aging temperature = Tensile test temperature	Aging temperature ≥ Tensile test temperature	Aging temperature ≥ Tensile test temperature
Aging temperature	Plural temperature points	Plural temperature points	Single temperature
Method for data processing			

CODE CSAES

In late 2007, proposals of code cases for new basket material were submitted to the Power Generation Code Committee of the JSME from four engineering companies. These code cases were consisted of 4 types of aluminum alloys and one type of borated stainless steel as summarized in Table 2. Chemical compositions of aluminum alloys are shown in Table 3.

The Code Committee assigned the Subgroup on Spent Fuel Storage Facilities within the Subcommittee on Nuclear Power to evaluate the cases. The Subgroup established the Working Group on Packaging Material Evaluation in January 2008 to entrust the assessment of these applications, with nine experts from universities, research organizations, material manufacturers and an electric company and three observers from the Subgroup. The Working Group enthusiastically met eight times in a half year to investigate and discuss the applications, and reported to the Subgroup that applied materials were complying with the guidelines in July.
The code cases were approved by the Subgroup in the end of July 2008, by the Subcommittee in August, and approved for public comments by the Code Committee in December. With no public comment, the code cases were finally approved the Code Committee in March 2009, and published.

Table 2. Code cases of aluminum alloy

Code Numbers	Materials	Descriptions
JSME S FA-CC-001	Borated aluminum alloy	1 % borated Type A-6061-T6 and –T651 aluminum
JSME S FA-CC-002	Aluminum alloy	Type A-6061-T6 and –T651 aluminum
JSME S FA-CC-003	Aluminum alloy	Type A-5083FH-O aluminum
JSME S FA-CC-004	Borated stainless steel sheet	1 % borated Type 304 stainless steel
JSME S FA-CC-005	Borated aluminum alloy	Up to 9 % B_4C added Type A6N1 aluminum (ASME Code case N-673)

Table 3. Chemical compositions of aluminum alloy in the code cases

Code	Chemical composition (mass %)										
	Base aluminum alloy (100%)										Additional component
	Si	Fe	Cu	Mu	Mg	Cr	Zn	Ti	B	Al	
M1	0.4≤ ≤0.8	≤0.7	0.15≤ ≤0.40	0≤0.15	0.8≤ ≤1.2	0.04≤ ≤0.35	≤0.25	≤0.15	0.8≤ ≤1.2	rest	--
M2	0.4≤ ≤0.8	≤0.7	0.15≤ ≤0.40	0≤0.15	0.8≤ ≤1.2	0.04≤ ≤0.35	≤0.25	≤0.15	--	rest	--
M3	≤0.40	≤0.40	≤0.10	0.40≤ ≤1.0	4.0≤ ≤4.9	0.05≤ ≤0.25	≤0.25	≤0.15	--	rest	--
M4	0.4≤ ≤0.9	≤0.35	≤0.35	≤0.5	0.4≤ ≤0.8	≤0.30	≤0.25	≤0.10	--	rest	B+C 1.5≤ ≤9

The applications for the code case were supplemented with explanatory documents, data sets in various aspects such as:

- Material specification including chemical compositions, mechanical properties, heat treatment, conditions for use, etc.
- Explanatory documents on macro/micro metal structure, corrosion resistance, irradiation effect, manufacturing method, quality assurance, patients and licenses, etc.,
- Data sets of mechanical and thermal tests on ductility (Charpy impact test and/or fracture toughness test), hardness, tensile, creep and creep rapture, thermal expansion coefficient, thermal conductivity, temperature conductivity, Young's modulus and Poisson's ratio, with specifications of the specimen used,
- Data sets of allowable stresses, together with data processing methods,
- Explanatory document on the basket design, and
- Reference documents to support explanation or justification.

The experts in Working Group intensively investigated these documents and data whether they satisfied the recommendations in the guidelines following the check list provided by the working group chair. Though some items were required supplementary data or explanations, finally the Working Group concluded that all the cases were acceptable.

There were differences in consideration of overaging effect among the code cases.

Material M1 and M2

Material M1 and M2 use the same base aluminum alloy and the same heat treatment, but difference lies in whether borated or not. For these materials, specimens for tensile test were overaged at the same temperature and different overaging times, i.e. at different Larson and Miller Parameters (LMPs), and tested at each temperature. This data acquisition method corresponds to Method 2 in Table 2. Then, allowable stress values were set at the LMP value of 60 years storage period.

So, allowable stress values for each temperature were set as:

$$Sa = So \times A_1 \times A_2 \quad \cdots\cdots \quad (Eq.1)$$

Where, Sa is an allowable stress value for each temperature (Sm, S, Sy and Su)

So is the basic stress value at room temperature

A_1 is the reduction factor due to temperature (i.e. trend curve coefficient derived from test data at all temperatures)

A_2 is the reduction factor due to overaging (i.e. ratio between aged material strength and overaged material strength at each temperature)

Samples of the stress reduction factor due to overaging are shown in Fig.1.

The above LMP value is specified as a part of the material specifications. This LMP value is dependent on the DPDMC design. LMP is defined as below:

$$LMP = (T + 273) \times (20 + \log t) \quad \cdots\cdots \quad (Eq.2)$$

Where, T is a material temperature in deg-C

t is the storage time in hour at that temperature

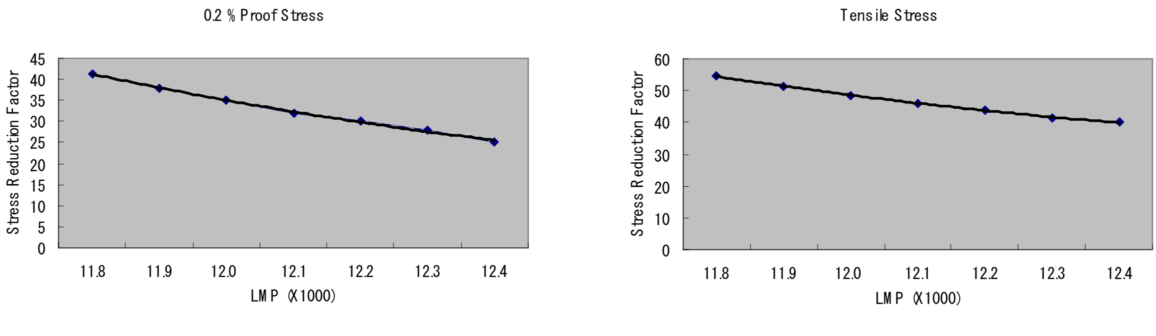


Figure 1. Sample of stress reduction factors due to overaging

Material M3

As Material M3 is a fully annealed alloy, no consideration on the effect of overaging can paid basically. On the other hand, since chemical composition of this material is Mg rich, the strength increases in progress with the storage period, or with descend of temperature of material during storage due to deposition of Mg in the metal structure.

In this case, to be conservative tensile test data with short time heated specimen were used to the basis for allowable stress value setting, and reduction factor A_2 in Eq.1 was set as unique (1). No LMP is specified in the material specifications.

Material M4

Material M4 is manufactured by powder metallurgy and no heat treatment is applied. The applicant explained that the overaging effect is negligible with test data with specimens overaged up to the same LMP value of 60 years storage period. As a result no overaging effect (i.e. reduction factors) was considered in setting the allowable stress values, but the LMP was specified in the material specifications. The reduction factor A_2 was also set as unique for this material.

The creep characteristics of these materials have been well defined through the data provided by applicants, and no specific argument was made in the Working Group. For each material the creep rapture stress data was incorporated in establishing the allowable tensile strength values, and creep constitutive equations obtained would be used in structural strength evaluation to calculate creep strain during the storage.

Though they are basically ductile material, three alloys did not satisfy the lateral expansion criteria in Charpy impact test. As a result, fracture mechanics evaluation as specified in the JSME Rules would be required in the basket design evaluation for these materials.

Allowable stress values for aluminum alloys in the approved code cases are exhibited in Fig.2.

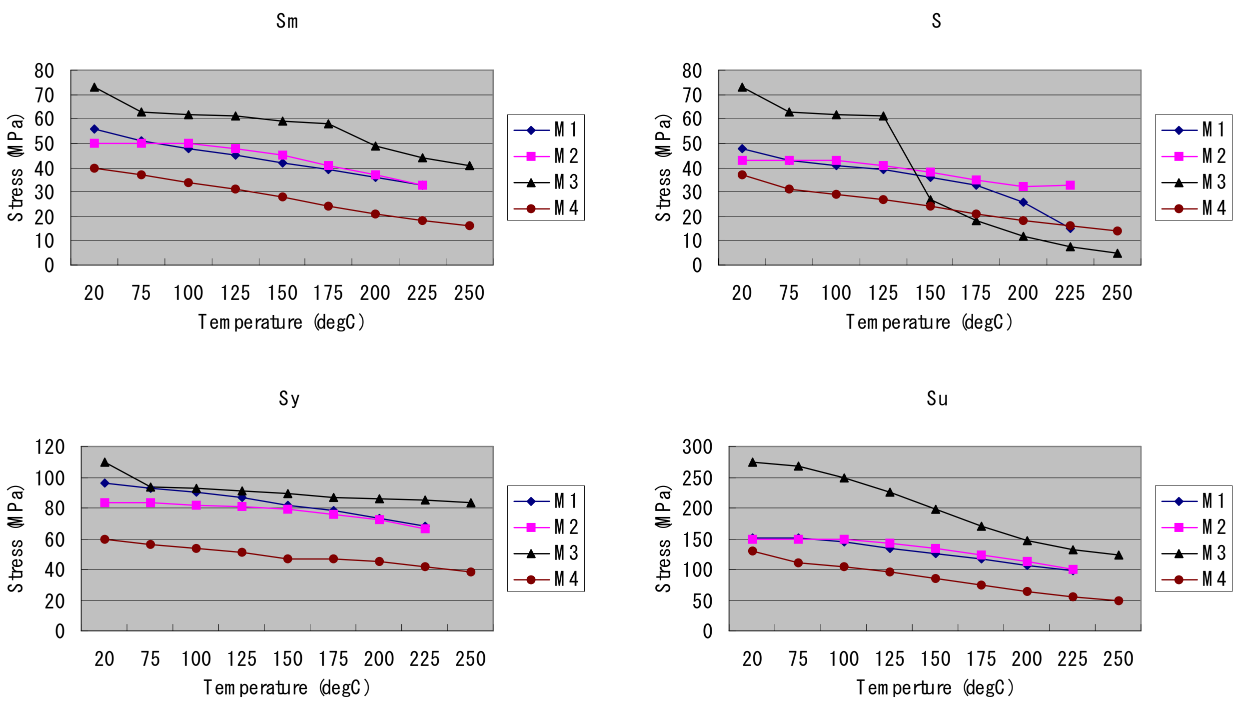


Figure 2. Allowable stress values from code cases of aluminum alloys

The code case of borated stainless steel was easily approved, since no creep nor overaging could be envisaged due to the storage temperature range, and corrosion was negligible due to the inert gas environment during transport and storage.

CONCLUSIONS

The holistic approach in licensing of DPDMCs in Japan is now supported by the voluntary standard established by the Atomic Energy Society of Japan and the design and construction rules established by the Japan Society of Mechanical Engineers. Further more, new basket materials, such as aluminum alloy, borated aluminum alloy and borated stainless steel, which maintain integrity during long-term storage and transport before and after storage, are available as approved code cases by JSME. In these rules and code cases, especially for aluminum alloys, effects of creep and overaging of the material during the storage and on the transport after storage are taken into account.

Efforts to establish and maintain these standard and rules have supported the establishment of spent fuel interim storage enterprise in Japan, and bear fruits as follows:

- The permission of spent fuel storage enterprise, as stipulated in the Law for the Regulations of Nuclear Source Material, Nuclear Fuel Material and Reactors, was granted on 13 May 2010,
- The design and construction methods of the storage facility was approved on 27 August 2010, which includes the construction permit of DPDMCs as the spent fuel storage components, and
- The transport package design approvals for two types of DPDMC were submitted on 31 August 2010.

ACKNOWLEDGMENTS

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REFERENCES

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