Proceedings of the 15th International Symposium on the Packaging and Transportation of Radioactive Materials
PATRAM 2007
October 21-26, 2007, Miami, Florida, USA

DEVELOPMENT AND DISCUSSION OF DESIGN CODE FOR BASKETS MADE OF ALUMINUM ALLOYS AND BORATED ALUMINUM ALLOYS FOR TRANSPORT/STORAGE PACKAGINGS

Makoto Hirose
Nuclear Fuel Transport Co., Ltd.

Toshiari Saegusa
Central Research Institute of Electric Power Industry

Kenji Miyata
The Kansai Electric Power Co., Inc.

Takahisa Nakatani
OCL Corporation

Hiroshi Akamatsu
Kobe Steel, Ltd.

Tomofumi Yamamoto
Mitsubishi Heavy Industries, Ltd.

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 August, 2001. The Rules nominated only conventional steels as materials for the basket of packagings. On the other hand most of current designs proposed for transport/storage packaging in Japan adopt aluminum alloy or borated aluminum alloy as a material of the basket to enjoy merits of better heat conduction and component weight reduction. Therefore a material and design code for such basket has been anticipated eagerly.
To meet this need the Subgroup on Spent Fuel Storage Facilities of the JSME started development of the rules on aluminum alloy basket in April, 2004. After two years of concentrated work by members of the Subgroup, a draft of the rule, which will be a part of proposed revision of the Rules on Transport/Storage Packagings, is at the final stage of approval process in the Committee.
The proposed rules for aluminum alloy basket consist of the following three parts,

(1) Requirements for the material of aluminum alloy for basket,
(2) Requirements for the design of aluminum alloy basket, and
(3) Guidelines for the application of aluminum alloy as a new material for the spent fuel transport/storage packaging basket.

The design rules limit the creep strain during a design life up to 60 years not to exceed 0.4 %, though they allow to use the material in a temperature range of creep growth. While the allowable stress limits against long term loadings are set with creep effects in consideration, the limits against short term loadings such as package drop in the transport after the storage are not.

The guidelines address methods to establish allowable stress values with consideration of creep and over-aging (reversion) of age hardening aluminum alloys together with methods on testing the material and processing collected material data.
In this paper details of the rules and major discussions on them within the JSME Committees are introduced.

1. INTRODUCTION

As presented in the PATRAM2004*[1], the Subgroup on Spent Fuel Storage Facilities within the Subcommittee on Nuclear Power in the Committee for Power Equipment Code of the JSME started development of rules on design and construction for spent fuel transport and storage equipment in 1999 in order to contribute to future construction of spent fuel storage facilities. The following rules have been published so far.

- Rules on Transport/Storage Packagings for Spent Nuclear Fuel (March, 2002)
- Rules on Concrete Casks, Canister Transfer Machines and Canister Transport Casks for Spent Nuclear Fuel (December, 2003)

Meanwhile, the Recyclable-Fuel Storage Company is in preparation of the first Japanese spent fuel interim storage facility away from the reactors at Mutsu-City, Aomori Prefecture aiming commissioning in 2010. The application for a spent fuel storage enterprise was filed on 22nd March, 2007, and safety evaluations of the facility design is now underway. Several designs of transport/storage packagings for the facility are realized based on the above Rules. Though the Rules nominate only conventional steel materials for baskets, the most of current designs for the facility employ aluminum alloy or borated aluminum alloy (hereinafter referred as “aluminum alloys”) as basket material. Aluminum basket designs have the following merits, which can achieve better integrity of spent fuel cladding during storage and larger storage capacity per packaging.

- Better heat conduction property results in lower fuel cladding temperature, and,
- Smaller specific gravity results in lighter basket and reduces packaging weight.

On the other hand, as aluminum alloys will be used in the temperature range of creep growth or over-aging, development of design code for aluminum alloy basket considering these effects has been anticipated by the users of the Rules.
To satisfy the needs the Subgroup on Spent Fuel Storage Facilities started development of the rules on aluminum baskets in April, 2004. After two years of concentrated work by members the Subgroup provided a draft of the revised Rules on Transport/Storage Packagings including provisions on aluminum alloys in May, 2006. The draft was reviewed by the Subgroup on Materials (in charge of the Rules on Materials) and the Subgroup on Elevated Temperature Service (in charge of Rules on Design and Construction for Fast Breeder Reactors). Then the draft was reviewed by the Subcommittee on Nuclear Power and by the Committee for Power Equipment Codes, and approved to submit for the public review. During the public review only one comment was received. After the response to the comment the Rules will be approved for publication by the Committee, and will finally be published in the next spring.

2. OUTLINE OF THE RULES ON TRANSPORT/STORAGE PACKAGINGS

The Rules on Transport/Storage Packagings for Spent Nuclear Fuel consist of provisions for three major components of packagings, i.e., the containment vessel which contains radioactive

material, the basket which supports spent fuel assemblies and the trunnions to handle or secure the packaging. Requirements for each components are based on those for the similar components in the JSME Design & Construction Code or the Boiler and Pressure Vessel (B&PV) Code of the American Society of Mechanical Engineers (ASME) as shown in Table 1.
Rules on the material, design and construction of baskets are similar to those on the Core Support Structure of the JSME Code or Section III, Subsection NG of the ASME B&PV Code.

Table 1. Basis for Provisions of the Rules on Transport/Storage Packagings

Components	Basis for Provisions	
	JSME Design & Construction Code	ASME B&PV Code
Containment Vessel	Class 1 Vessel	Section III, Subsection NB or Subsection WB
Basket	Core Support Structure	Section III, Subsection NG
Trunnions	Class 1 Component Support Structure	Section III, Subsection NF

3. RULES ON ALUMINUM ALLOYS BASKETS

Rules for baskets made of aluminum alloys have been developed with consideration to the below characteristics of the basket design.

- Initial maximum basket temperature is in the range from 200 to 250 degC, but will decreases monotonously in the course of storage duration.
- A basket is not a pressure retaining component but a supporting structure, and mechanical loadings applied to during storage are very small. Only a significant loading occurs at the drop accident of package during transport or handling.
- Deformation of the basket should be kept negligible small in order to maintain intact sub-criticality configuration.

Specific considerations in the rules for aluminum baskets are addressed in the followings.

3.1 Material Requirements

A step-wise provision of fracture toughness requirement is prescribed for aluminum alloys to ensure their ductility.

(1) Step 1: Charpy V-notch Impact Test below the minimum service temperature,
(2) Step 2: If the Step 1 is not complied, then Dynamic Tear Test per ASTM E604-83 below the minimum service temperature,
(3) Step 3: If the Step 2 is not complied, then Dynamic Fracture Toughness Test per JSME S001-1981 or ASTM E1820-05a to confirm that its fracture toughness value exceeds the stress concentration factors during storage, transport and handling of the package.

3.2 Design Requirements

Stress and strain limits for the aluminum baskets are tabulated in Table 2 together with the limits for baskets made of conventional steels.
Major differences from the limits for conventional baskets are;

- Stress in the Level A and Level B Service Conditions and against long term loadings are limited based on the allowable tensile strength values which incorporates 100,000 hour creep strength. Creep strains are also limited up to 0.2% for membrane creep strain and 0.4% for membrane and bending creep strain.

- If stress intensity limit of 1.5Sm is exceeded against long term and short term combined loadings, then the range of stress intensity due to short term cyclic loadings is limited below 3Sm to keep the component within shakedown region. Creep strains in this case are also limited not to exceed 0.2%/0.4%.
- Stress intensities in the Level C Service Conditions are limited lower compared with conventional materials to maintain consistency to the Rules on Fast Breeder Reactors.
- Stress intensity limits for austenitic stainless steel in the Level D Service Conditions are not adopted.

In comparison with the Rules on Fast Breeder Reactors the below simplifications are adopted.

- Allowable tensile strength values S, not St which is temperature and time dependent values used in the Rules on Fast Breeder Reactors, is employed as a basis for stress intensity limits for the long term loadings.
- Creep strains are limited not to exceed 0.2%/0.4%.
- No stress limit for long term loadings in the Level C and Level D Service Conditions is set, since only short term loadings are anticipated in these conditions.

Table 2. Stress and Strain Limits for the Aluminum Alloy Baskets Compared with the Conventional Material Baskets (1/2)

Service Conditions	Load-ings	Stress	Aluminum Alloy Basket	Conventional Basket
Level A and Level B	Long term	Stress intensity and Strain	• Pm ≤ S • Pm + Pb ≤ KoS • εmc ≤ 0.002 • εmc + εbc ≤ 0.004	
		Pure shear	• τ ≤ 0.6S	
		Bearing	• σp ≤ S	
		Compression	• σb(pri) ≤ fc • σb(prim+scnd) ≤ 1.5fc	
	Long term + Short term	Stress intensity and Strain	• Pm+Pm* ≤ Sm • Pm+Pm*+Pb+Pb* ≤ 1.5Sm • Pm+Pm*+Pb+Pb*+Q+Q* ≤ 1.5Sm In case when 1.5Sm exceeded, • [Pm*+Pb*+Q*]R ≤ 3Sm • εmec ≤ 0.002 • εmec + εbec ≤ 0.004	• Pm+Pm* ≤ Sm • Pm+Pm*+Pb+Pb* ≤ 1.5Sm • [Pm+Pm*+Pb+Pb*+Q+Q*]R ≤ 3Sm
		Pure shear	• $\tau + \tau^*$ ≤ 0.6Sm	• $\tau + \tau^*$ ≤ 0.6Sm
		Bearing	• σp+σp* ≤ Sy (1.5Sy)	• σp+σp* ≤ Sy (1.5Sy)
		Compression	• σb+σ b*(prim) ≤ fc • σb+σ b* (prim+scnd) ≤ 1.5fc	• σb+σ b*(prim) ≤ fc • σb+σ b* (prim+scnd) ≤ 1.5fc

Table 2. Stress and Strain Limits for the Aluminum Alloy Baskets Compared with the Conventional Material Baskets (2/2)

Service Conditions	Load-ings	Stress	Aluminum Alloy Basket	Conventional Basket
Level C	Long term + Short term	Stress intensity and Strain	• Pm+Pm*≤ 1.2Sm • Pm+Pm*+Pb+Pb*≤ 1.8Sm • Pm+Pm*+Pb+Pb*+Q+Q* ≤ 1.5Sm In case when 1.5Sm exceeded, • [Pm*+Pb*+Q*]R≤ 3Sm • εmec ≤ 0.002 • εmec＋εbec≤ 0.004	• Pm+Pm*≤ 1.5Sm • Pm+Pm*+Pb+Pb*≤ 2.25Sm
		Pure shear	• $\tau+\tau$*≤ 0.9Sm	• $\tau+\tau$*≤ 0.9Sm
		Bearing	• σp+σp*≤ 1.5Sy (2.25Sy)	• σp+σp*≤ 1.5Sy (2.25Sy)
		Compression	• σb+σ b*(prim)≤ 1.5fc • σb+σ b* (prim+scnd) ≤ 1.5fc	• σb+σ b*(prim)≤ 1.5fc • σb+σ b* (prim+scnd) ≤ 1.5fc
Level D	Long term + Short term	Stress intensity	• Pm+Pm*≤ (2/3)Su • Pm+Pm*+Pb+Pb*≤ Su • In case of the cyclic loads, [Pm*+Pb*+Q*]R≤ 3Sm	For austenitic stainless steels, • Pm+Pm*≤ (2/3)Sm • Pm+Pm*+Pb+Pb*≤ Su For other than austenitic stainless steels, • Pm+Pm* ≤ MIN(2.4Sm, (2/3)Su) • Pm+Pm*+Pb+Pb* ≤ MIN(3.6Sm, Su)
		Pure shear	• $\tau+\tau$*≤ 1.2Sm	• $\tau+\tau$*≤ 1.2Sm
		Bearing	• σp+σp*≤ 2Sy (3Sy)	• σp+σp*≤ 2Sy (3Sy)
		Compression	• σb+σ b*(prim)≤1.5fc* • σb+σ b* (prim+scnd) ≤1.5fc	• σb+σ b*(prim)≤1.5fc* • σb+σ b* (prim+scnd) ≤1.5fc

Notes – Pm: general primary membrane stress due to long term loadings, Pm: general primary membrane stress due to short term loadings, Pb: primary bending stress due to long term loadings, Pb*: primary bending stress due to short term loadings, Q: secondary stress due to long term loadings, Q*: secondary stress due to short term loadings, εmc: membrane creep strain due to long term loadings, εbc: bending creep strain due to long term loadings, εmec: cumulative membrane creep strain including accelerated creep caused by stress relocation after short time loadings, εbec: cumulative bending creep strain including accelerated creep caused by stress relocation after short time loadings, τ: average shear stress due to long term loadings, τ*: average shear stress due to short term loadings, σp: average compression stress due to long term loadings, σp*: average compression stress due to short term loadings, σb: average bearing stress due to long term loadings, σb*: average bearing stress due to short term loadings, Ko: limiting factor, Sm: design stress intensity values, Sy: design yield stress values, Su: design tensile stress values, S: allowable tensile stress values, fc: allowable compression stress values and [σ]R: range of stress intensity for stress σ in loading cycle.*

3.3 Guidelines for New Aluminum Alloys

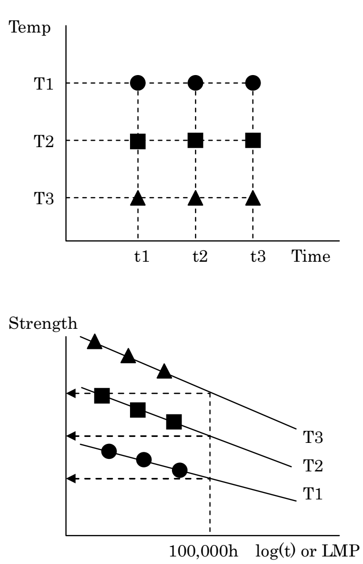
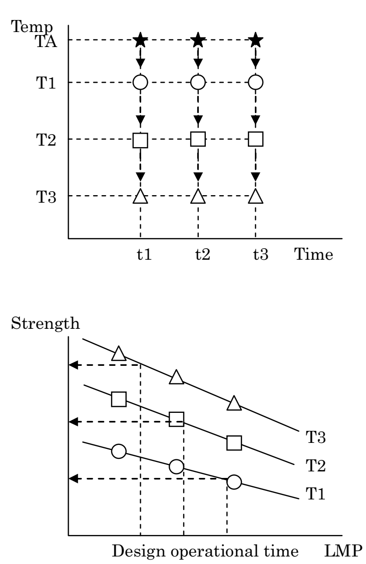
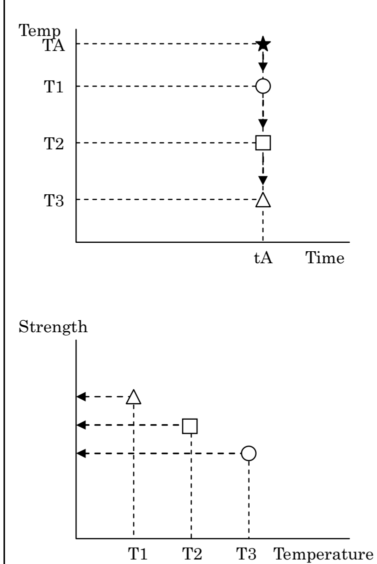
Any new aluminum alloy shall be approved as a proper material for the basket by the Subgroup on Spent Fuel Facilities in advance to use. Approved material will be published as a Code Case, and will be adopted into the Rule at the time of the next revision.

The Subgroup has provided “Guidelines for the application of aluminum alloy as a new material for the spent fuel transport/ storage packaging basket” as a part of a mandatory appendix of the Rule to help applicants for the code case. The Guidelines have been developed from the basic guidelines in the Rules on Materials of the JSME (to be published), and recommend to include the following information in the application;

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

The guidelines also recommend three methods for data acquisition and processing for aged aluminum alloy as summarized in Table 3.

Table 3. Examples of data acquisition and processing method for aged aluminum alloy

	Method 1 Aging duration is taken as a parameter (1)	**Method 2** Aging duration is taken as a parameter (2)	**Method 3** 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			

(1) Method 1: Specimens are over-aged at time (t1, t2, t3) × temperature (T1, T2, T3) matrix and subjected to tensile tests at temperature (T1, T2, T3). From the test results tensile strength values corresponds to 100,000h and temperature (T1, T2, T3) are derived.
(2) Method 2: Specimens are over-aged at time (t1, t2, t3) × temperature TA and subjected to tensile tests at temperature (T1, T2, T3), where TA ≥ T1, T2, T3. From the test results the tensile strength values corresponds to storage duration are derived.
(3) Step 3: Specimens are over-aged at temperature TA which corresponds to maximum storage duration (maybe fully over-aged). Tensile tests at temperature (T1, T2, T3) give conservative strength values at temperature (T1, T2, T3).

4. DISCUSSIONS

Major comments from the Subgroup on Elevated Temperature Service, the Subgroup on Material or the Subcommittee for Nuclear Power during the review and responses by the Subgroup on Spent Fuel Storage Facilities are introduced below.

Comment: Brand new rules should be established and published after several design and construction experiences have been obtained.
Response: The Subgroup has judged that it is important to publish the Rules before the first realization of design or construction in order to enhance and accelerate licensing procedures of a facility with new concept.

Comment: It is hard to review new rules without examples of material, design or evaluation results.
Response: Several examples from proposed designs including the following alloys were exhibited to the review members. Some examples of material, design are presented in the PATRAM2007*[2, 3)].

- A5083FH-O, not borated
- A6051-T651 based, 1% B added
- ASME Code Case N673 (A6N01), up to 5% B_4C added

Comment: What is the justification for the creep strain limitation of 0.2/0.4%?
Response: It has been demonstrated by tensile tests with pre-creep-strained specimen that small creep strain in this range gives no effect on the yield or tensile strength against short term loadings*[4)].

Comment: When the creep strain is limited to negligible small, rules on design for elevated temperature service could be simplified, or even no consideration can be taken.
Response: The Subgroup agrees the direction of comment. However, since this is the first rules on the aluminum alloys for elevated temperature service, the Subgroup has chosen to provide the most careful provisions to prevent creep damage for the time being. After enough experiences gained, simplification may be considered.

Comment: The Rules on Materials will provide comprehensive guidelines for application of new materials addressing that creep characteristics or aging characteristics to be considered. So, the guidelines in the Rules can be omitted.
Response: The Guidelines in the Rules on Materials are too generic. For user friendliness the Subgroup considered it is better to provide guidelines specific to aluminum alloys.

Comment: In case of aged aluminum alloys the Guidelines recommend to provide allowable stress values in temperature and time dependent manner. Allowable stress values should be a unique value for each temperature, and the effect of over-aging on the allowable stress shall be given as stress reduction factors.
Response: Among the JSME Codes both cases exist. The Subcommittee on Nuclear Power takes up this matter as an issue to be settled.

5. CONCLUSIONS

The design code for baskets made of aluminum alloys and borated aluminum alloys for transport/storage packagings, which is the first of its kind, has been established by the Subgroup on Spent Fuel Facilities in the Subcommittee on Nuclear Power within the Committee for Power Equipment Codes, and ready for publication as a revision of the Rules on Transport/Storage Packagings for Spent Nuclear Fuel of the Codes for Construction of Spent Nuclear Fuel Storage Facilities.
The code is expected to be a basis for the transport/storage packagings for the Mutsu Recyclable Fuel Storage Facility which is scheduled to be commissioned in 2010, and to assist licensing of these packagings.

6. ACKNOWLEDGMENTS

The authors wish to thank the members of the Committee, Subcommittee and other Subgroups for their enthusiastic reviews and helpful comments in the preparation of the Rules.

7. REFERENCES

1) Hirose, M., Aritomi, M., Saegusa, T., et.al., “Standards for Transport and Storage Components Established by The Atomic Energy Society of Japan and The Japan Society of Mechanical Engineers”, PATRAM2004.
2) Maeguchi, T., et.al, “Development and Reliability Verification of Aluminum Alloys for Basket of Transport and Storage Cask for Spent Nuclear Fuel”, PATRAM2007.
3) Shimojo, J., et.al., “Development of Borated Aluminum Material fro Basket of Transport/ Storage Casks”, PATRAM2007.
4) Nuclear Power Engineering Corporation, “Investigation Report on the Recycle Fuel Resource Storage Technology (Demonstration Tests on Metal Cask Storage Technology), -Fiscal Year 2002”, March 2003.