be checked for safety against buckling. For the special case of cylindrical monobloc shells, the following equation shall be used:

\[ P_D = \frac{E (Y - 1)^3}{40(1 - \nu^2) Y^3} \quad \text{(KD-222.1)} \]

but in no case shall exceed the value of \( P_D \) given by the equation in KD-221.1.

**KD-230 ELASTIC–PLASTIC ANALYSIS**

The equations for cylindrical and spherical shells in KD-220 need not be used if a nonlinear elastic-plastic analysis (KD-231) is conducted using numerical methods such as elastic-plastic finite element or finite difference analysis for the loadings described in Table KD-230.1 and Table KD-230.2. When elastic-plastic analysis is used, the Designer shall also comply with KD-232 through KD-236.

**KD-231 ELASTIC–PLASTIC ANALYSIS METHOD**

Protection against plastic collapse is evaluated by determining the plastic collapse load of the component using an elastic-plastic stress analysis. The plastic collapse load on the component is established by applying a load factor to the calculated plastic collapse load. Elastic-plastic stress analysis closely approximates the actual structural behavior by considering the redistribution of stress that occurs as a result of inelastic deformation (plasticity) and deformation characteristics of the component.

**KD-231.1 Elastic–Plastic Numerical Analysis.** The plastic collapse load can be obtained using a numerical analysis technique (e.g., finite element method) by incorporating an elastic-plastic material model (see KM-620 or KM-630, as appropriate) to obtain a solution. The effects of nonlinear geometry shall be considered in this analysis. The plastic collapse load is the load that causes overall structural instability. This point is indicated by the inability to achieve an equilibrium solution for a small increase in load (i.e., the solution will not converge).

**KD-231.2 Elastic–Plastic Acceptance Criteria.** The acceptability of the component using elastic-plastic analysis shall be demonstrated by evaluation of the plastic collapse load. The plastic collapse load is taken as the load that causes structural instability. This shall be demonstrated by satisfying the following criteria:

(a) Global Criteria. A global plastic collapse load is established by performing an elastic-plastic analysis of the component subject to the specified loading conditions.

The concept of Load and Resistance Factor Design (LRFD) is used as an alternative to the rigorous computation of a plastic collapse load to design a component. In this procedure, factored loads that include a load factor to account for uncertainty and the resistance of the component to these factored loads are analyzed using elastic-plastic analysis (see Table KD-230.4).

(b) Service Criteria. Service criteria that limit the potential for unsatisfactory performance shall be analyzed at every location in the component when subject to the design loads (see Table KD-230.4). Examples of service criteria are limits on the rotation of a mating flange pair to avoid possible flange leakage concerns, and limits on tower deflection that may cause operational concerns. In addition, the effect of deformation of the component on service performance shall be evaluated at the design load combinations. This is especially important for components that experience an increase in resistance (geometrically stiffen) with deformation under applied loads such as elliptical or torispherical heads subject to internal pressure loading. The plastic collapse criteria may be satisfied but the component may have excessive deformation at the derived design conditions. In this case, the design loads may have to be reduced based on a deformation criterion. Examples of some of the considerations in this evaluation are the effect of deformation on

(1) piping connections
(2) misalignment of trays, platforms, and other internal or external appurtenances
(3) interference with adjacent structures and equipment
(4) load-bearing interfaces

If applicable, the service criteria shall be specified in the User’s Design Specification.

(c) Local Criteria. A component shall satisfy the local criteria requirements given in KD-232.

(**see KG-311**)
<table>
<thead>
<tr>
<th>Loading Condition</th>
<th>Design Loads</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pressure Testing Assembly loads</td>
<td>Dead load of component plus insulation, fireproofing, installed internals, platforms, and other equipment supported from the component in the installed position</td>
</tr>
<tr>
<td></td>
<td>Piping loads including pressure thrust</td>
</tr>
<tr>
<td></td>
<td>Applicable live loads excluding vibration and maintenance live loads</td>
</tr>
<tr>
<td></td>
<td>Pressure and fluid loads (water) for testing and flushing equipment and piping unless a pneumatic test is specified</td>
</tr>
<tr>
<td></td>
<td>Wind loads</td>
</tr>
<tr>
<td>Normal Operation Assembly loads</td>
<td>Dead load of component plus insulation, refractory, fireproofing, installed internals, catalyst, packing, platforms, and other equipment supported from the component in the installed position</td>
</tr>
<tr>
<td></td>
<td>Piping loads including pressure thrust</td>
</tr>
<tr>
<td></td>
<td>Applicable live loads</td>
</tr>
<tr>
<td></td>
<td>Pressure and fluid loading during normal operation</td>
</tr>
<tr>
<td></td>
<td>Thermal loads</td>
</tr>
<tr>
<td></td>
<td>Loads imposed by the motion of the structure to which the vessel is fastened</td>
</tr>
<tr>
<td>Normal Operation Plus Occasional</td>
<td>Dead load of component plus insulation, refractory, fireproofing, installed internals, catalyst, packing, platforms, and other equipment supported from the component in the installed position</td>
</tr>
<tr>
<td>[Note (1)]</td>
<td>Piping loads including pressure thrust</td>
</tr>
<tr>
<td></td>
<td>Applicable live loads</td>
</tr>
<tr>
<td></td>
<td>Pressure and fluid loading during normal operation</td>
</tr>
<tr>
<td></td>
<td>Thermal loads</td>
</tr>
<tr>
<td></td>
<td>Wind, earthquake, or other occasional loads, whichever is greater</td>
</tr>
<tr>
<td></td>
<td>Loads due to wave action</td>
</tr>
<tr>
<td></td>
<td>Loads imposed by the motion of the structure to which the vessel is fastened</td>
</tr>
<tr>
<td>Abnormal or Start-up Operation Plus</td>
<td>Dead load of component plus insulation, refractory, fireproofing, installed internals, catalyst, packing, platforms, and other equipment supported from the component in the installed position</td>
</tr>
<tr>
<td>Occasional [Note (1)]</td>
<td>Piping loads including pressure thrust</td>
</tr>
<tr>
<td></td>
<td>Applicable live loads</td>
</tr>
<tr>
<td></td>
<td>Pressure and fluid loading associated with the abnormal or start-up conditions</td>
</tr>
<tr>
<td></td>
<td>Thermal loads</td>
</tr>
<tr>
<td></td>
<td>Wind loads</td>
</tr>
</tbody>
</table>

NOTE:
(1) Occasional loads are usually governed by wind and earthquake; however, other load types such as snow and ice loads may govern (see ASCE/SEI 7).
The following assessment procedure is used to determine the acceptability of a component using elastic–plastic stress analysis.

**Step 1.** Develop a numerical model of the component including all relevant geometry characteristics. The model used for the analysis shall be selected to accurately represent the component geometry, boundary conditions, and applied loads. In addition, refinement of the model around areas of stress and strain concentrations shall be provided. The analysis of one or more numerical models may be required to ensure that an accurate description of the stresses and strains in the component is achieved.

**Step 2.** Define all relevant loads and applicable load cases. The loads to be considered in the design shall include, but not be limited to, those given in Table KD-230.1.

**Step 3.** An elastic–plastic material model shall be used in the analysis. The von Mises yield function and associated flow rule should be utilized if plasticity is anticipated. A material model that includes hardening or softening, or an elastic–perfectly plastic model (see Article KM-6) may be utilized. A true stress–strain curve model that includes temperature dependent hardening behavior is provided in KM-620. The effects of nonlinear geometry shall be considered in the analysis.

**Step 4.** Determine the load combinations to be used in the analysis using the information from Step 2 in conjunction with Table KD-230.4. Each of the indicated load cases shall be evaluated. The effects of one or more loads not

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**Table KD-230.2 Load Descriptions**

<table>
<thead>
<tr>
<th>Design Load Parameter</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$P_D$</td>
<td>Internal and external design pressure</td>
</tr>
<tr>
<td>$P_S$</td>
<td>Static head from liquid or bulk materials (e.g., catalyst)</td>
</tr>
<tr>
<td>$P_t$</td>
<td>Hydrostatic test pressure determined in Article KT-3</td>
</tr>
<tr>
<td>$D$</td>
<td>Dead weight of the vessel, contents, and appurtenances at the location of interest, including the following: Weight of vessel including internals, supports (e.g., skirts, lugs, saddles, and legs), and appurtenances (e.g., platforms, ladders, etc.) Weight of vessel contents under operating and test conditions Refractory linings, insulation Static reactions from the weight of attached equipment, such as motors, machinery, other vessels, and piping</td>
</tr>
<tr>
<td>$L$</td>
<td>Appurtenance live loading Effects of fluid momentum, steady state and transient</td>
</tr>
<tr>
<td>$L_A$</td>
<td>Floating transporter acceleration loads due to spectral motion response determined in KD-237</td>
</tr>
<tr>
<td>$E$</td>
<td>Earthquake loads (see ASCE/SEI 7 for the specific definition of the earthquake load, as applicable)</td>
</tr>
<tr>
<td>$W$ [Note (1)]</td>
<td>Wind loads</td>
</tr>
<tr>
<td>$W_A$</td>
<td>Assembly loads (e.g., shrink fit, wire winding, sealing preload)</td>
</tr>
<tr>
<td>$W_{pt}$ [Note (1)]</td>
<td>Pressure test wind load case. The design wind speed for this case shall be specified by the Owner-User.</td>
</tr>
<tr>
<td>$S_S$</td>
<td>Snow loads</td>
</tr>
<tr>
<td>$T$</td>
<td>Self-restraining load case (i.e., thermal loads, applied displacements). This load case does not typically affect the collapse load, but should be considered in cases where elastic follow-up causes stresses that do not relax sufficiently to redistribute the load without excessive deformation.</td>
</tr>
</tbody>
</table>

**Table KD-230.3 Combination for Analysis Exemption of Hydrostatic Test Criterion**

<table>
<thead>
<tr>
<th>Ratio of Hydrostatic Test Pressure to Design Pressure</th>
<th>Ratio of Yield Strength to Tensile Strength</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.25</td>
<td>≥0.612</td>
</tr>
<tr>
<td>1.30</td>
<td>≥0.653</td>
</tr>
<tr>
<td>1.35</td>
<td>≥0.694</td>
</tr>
<tr>
<td>1.40</td>
<td>≥0.799</td>
</tr>
<tr>
<td>143</td>
<td>≥0.910</td>
</tr>
</tbody>
</table>

**NOTE:**
(1) The wind loads, $W$ and $W_{pt}$, are based on ASCE/SEI 7 wind maps and probability of occurrence. If a different recognized standard for wind loading is used, the User’s Design Specification shall cite the standard to be applied and provide suitable load factors if different from ASCE/SEI 7.
acting shall be investigated. Additional load cases for special conditions not included in Table KD-230.4 shall be considered, as applicable.

Step 5. Perform an elastic–plastic analysis for each of the load cases defined in Step 4. If convergence is achieved, the component is stable under the applied loads for this load case. Otherwise, the component configuration (i.e., thickness) shall be modified or applied loads reduced and the analysis repeated.

(a) Each analysis used with respect to KD-232.1 shall use the elastic–plastic stress–strain model in KD-231.4. Nonlinear geometry shall be used in the analysis.

(b) The following evaluation shall be performed using two independent elastic–plastic analyses for the following loading conditions:

1. all loads listed as local criteria in Table KD-230.4.
2. a series of applied loads as described in KD-234. The same loading histogram needed to demonstrate compliance with KD-234 shall be used in this analysis. KD-350 contains guidance in development of that loading histogram.

(c) Loads from fabrication operations such as pressure testing, autofrettage, shrink fitting, and wire winding shall be included if they produce plastic deformation. These loads shall not be included in the evaluation of cold-forming damage, $D_{\text{form}}$.

(d) For a location in the component subject to evaluation, determine the principal stresses, $\sigma_1$, $\sigma_2$, $\sigma_3$, the equivalent stress, $\sigma_{eq}$, using eq. (KD-232.1) below, and the total equivalent plastic strain, $\epsilon_{p eq}$.

### KD-231.4 Elastic–Plastic Stress–Strain Curve Model

DELETED

### KD-232 PROTECTION AGAINST LOCAL FAILURE

In addition to demonstrating protection against plastic collapse as defined in KD-231, the local failure criteria below shall be satisfied.

#### KD-232.1 Elastic–Plastic Analysis Procedure

The following procedure shall be used to evaluate protection against local failure.

(a) Each analysis used with respect to KD-232.1 shall use the elastic–plastic stress–strain model in KD-231.4. Nonlinear geometry shall be used in the analysis.

(b) The following evaluation shall be performed using two independent elastic–plastic analyses for the following loading conditions:

1. all loads listed as local criteria in Table KD-230.4.
2. a series of applied loads as described in KD-234. The same loading histogram needed to demonstrate compliance with KD-234 shall be used in this analysis. KD-350 contains guidance in development of that loading histogram.

(c) Loads from fabrication operations such as pressure testing, autofrettage, shrink fitting, and wire winding shall be included if they produce plastic deformation. These loads shall not be included in the evaluation of cold-forming damage, $D_{\text{form}}$.

(d) For a location in the component subject to evaluation, determine the principal stresses, $\sigma_1$, $\sigma_2$, $\sigma_3$, the equivalent stress, $\sigma_{eq}$, using eq. (KD-232.1) below, and the total equivalent plastic strain, $\epsilon_{p eq}$.

### Table KD-230.4

<table>
<thead>
<tr>
<th>Load Combinations and Load Factors for an Elastic–Plastic Analysis</th>
</tr>
</thead>
<tbody>
<tr>
<td>Criteria</td>
</tr>
<tr>
<td>----------</td>
</tr>
<tr>
<td>Design Conditions</td>
</tr>
<tr>
<td>Global criteria</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>Local criteria</td>
</tr>
<tr>
<td>Serviceability criteria</td>
</tr>
<tr>
<td>Hydrostatic Test Conditions</td>
</tr>
<tr>
<td>Global criteria (1/Kut)</td>
</tr>
<tr>
<td>Serviceability criteria</td>
</tr>
</tbody>
</table>

GENERAL NOTES:

(a) The parameters used in the Load Combinations column are defined in Table KD-230.2.

(b) See KD-231.2 for descriptions of global and serviceability criteria.

(c) If the layered construction is applied, $K_{uteq}$ instead of $K_{ut}$ shall be used.

$$K_{uteq} = \left( \sum_{i=1}^{n} \left( K_{uteq_i}^2 \right) / \sum_{i=1}^{n} t_i \right)^{1/2}$$

where

- $K_{ut}$ = factor of upper limit for hydrostatic test pressure (see KT-312)
- $K_{uteq}$ = equivalent factor of upper limit for hydrostatic test pressure for layered construction
- $t_i$ = thickness of each layer
ARTICLE KG-3
RESPONSIBILITIES AND DUTIES

KG-300 GENERAL

The User, Manufacturer, and Inspector involved in the production and certification of vessels according to this Division have definite responsibilities and duties in meeting the requirements of this Division. The responsibilities and duties set forth in the following relate only to compliance with this Division, and are not to be construed as involving contractual relations or legal liabilities. Whenever User appears in this document, it may be considered to apply also to an Agent (e.g., designee or licensor) acting in his behalf.

KG-310 USER’S RESPONSIBILITY

It is the responsibility of the User or an Agent acting on behalf of the User to provide a User’s Design Specification for each pressure vessel to be constructed in accordance with this Division. The User’s Design Specification shall contain sufficient detail to provide a complete basis for design and construction in accordance with this Division. It is the User’s responsibility to specify, or cause to be specified, the effective Code Edition to be used for construction.

A single User’s Design Specification may be prepared to support the design of more than one pressure vessel when all details of the construction are identical for each pressure vessel. The location of installation shall be a single, specific jurisdiction, provided that all technical requirements of the User’s Design Specification are identical (see Article KG-1).

(a) The designated agent may be
   (1) a design agency specifically engaged by the User
   (2) the Manufacturer of a system for a specific service that includes a pressure vessel as a component that is purchased by the User, or
   (3) an organization that offers pressure vessels for sale or lease for specific services

(b) The User may select more than one designated agent to obtain the most experience-based advice in several areas of expertise when needed (e.g., design, metallurgy, fabrication, pressure relief).

(c) A designated agent may be self-appointed as such by accepting certain responsibilities of a designated agent, as in the case of vessels designed, manufactured (built) for stock, and intended for operation in a specific application.

(d) The Design Specification shall contain sufficient detail to provide a complete basis for Division 3 design and construction. Such requirements shall not result in design or construction that fails to conform with the rules of this Division.

KG-311 USER’S DESIGN SPECIFICATION

The User’s Design Specification shall include the following.

KG-311.1 Vessel Identification.
   (a) vessel number
   (b) name, function, purpose
   (c) service fluid

KG-311.2 Vessel Configuration.
   (a) shape
   (b) vertical or horizontal
   (c) nominal size or volume capacity
   (d) support method and location, including the foundation type and allowable loading, if applicable (see KD-110 and Article KD-7)
   (e) construction type
   (f) functions and boundaries of the items covered in KG-110
   (g) items furnished by Manufacturer
   (h) items furnished by User

KG-311.3 Controlling Dimensions.
   (a) outline drawings
   (b) openings, connections, closures
      (1) quantity of each
      (2) type and size
      (3) purpose
      (4) location, elevation, and orientation

KG-311.4 Design Criteria.
   (a) Design Pressure. Design pressure is the pressure at the top of the vessel and which, together with the applicable coincident (metal) temperature, is stamped on the nameplate. The pressure at the top of the vessel is also the basis for the pressure setting of the pressure relief devices protecting the vessel.
   (b) Design Temperature. The maximum mean metal temperature specified by the User, at design pressure. See KD-112. This is the design temperature that is to be stamped on the vessel.
   (c) More than one combination of design pressure and temperature may be specified.
(d) Minimum Design Metal Temperature (MDMT). The MDMT is the lowest temperature to which the vessel will be exposed when the primary stresses at any location in the vessel are greater than 6 ksi (40 MPa) (see KM-234). This temperature shall be determined considering the lowest process temperature to which the vessel will normally be exposed in service, including process upsets, dumps, jet impingement, etc. Also, see KD-112 and KD-113.

(e) Thermal gradients across the vessel sections.

KG-311.5 Operating Conditions.

(a) operating pressure at coincident fluid temperature.
The operating pressure is the maximum sustained process pressure that is expected in service. The operating pressure shall not exceed the design pressure. This pressure is expressed as a positive value, and may be internal or external to the vessel.

(b) upset and other combinations of operating pressures and coincident fluid temperature in sufficient detail to constitute an adequate basis for selecting materials

(c) proposed methods of heating and cooling, as well as those upset conditions that could lead to rapid heating or cooling of the vessel surfaces

(d) cyclic operating data and conditions

KG-311.6 Contained Fluid Data.

(a) phase (liquid, gaseous, dual)

(b) density

(c) unusual thermodynamic properties

(d) inlet and outlet fluid temperatures

(e) flow rates

(f) jet impingement streams

(g) statement if noxious, hazardous, or flammable

KG-311.7 Materials Selection.

(a) appropriate materials for resistance to process corrosion (specific or generic)

(b) corrosion/erosion allowance

(c) any information relating to possible deterioration of the selected construction materials due to environmental exposure. Examples of such concerns may be found in, but are not limited to, Section II, Part D, Nonmandatory Appendix A, Metallurgical Phenomena.

(d) if materials of construction include steels with a minimum specified yield strength greater than 120 ksi (827 MPa), state whether the material, when loaded, will be in contact with water or an aqueous environment at any time

When additional requirements are appropriate for the intended service, see KG-311.12.

KG-311.8 Loadings.

(a) The User shall specify all expected combinations of coincident loading conditions as listed in KD-110. These shall include reaction load vectors.

(b) This loading data may be established by

(1) calculation

(2) experimental methods

(3) actual measurement for similar conditions

(4) computer analysis

(5) published data

(c) The source of loading data shall be stated.

(d) For mobile vessels, loading conditions imposed by handling, transportation, or motion of the structure to which the vessel is fastened, including credible accidental loadings, shall be considered according to Article KD-1.

KG-311.9 Useful Operating Life Expected. State years and cycles.

KG-311.10 Fatigue Analysis.

(a) Fatigue analysis is mandatory for Division 3 vessels. It is the User’s responsibility to provide, or cause to be provided, information in sufficient detail so an analysis for cyclic operation can be carried out in accordance with Articles KD-3 and KD-4.

(b) The User shall state if leak-before-burst can be established based on documented experience with similar designs, size, material properties, and operating conditions (see KD-141) or if leak-before-burst is to be established analytically. The number of design cycles shall be calculated by Article KD-4 if leak-before-burst cannot be established.

(c) The User shall state whether through-thickness leaks can be tolerated as a failure mode for protective liners and inner layers. See KD-103, KD-810(f), and KD-931.

KG-311.11 Overpressure Protection. The User or his designated agent shall be responsible for the design, construction, and installation of the overpressure protection system. This system shall meet the requirements of Part KR. Calculations, test reports, and all other information used to justify the size, location, connection details, and flow capacity for the overpressure protection system shall be documented in the User Design Specification (see KR-100).

KG-311.12 Additional Requirements. The User shall state in the User’s Design Specification what additional requirements are appropriate for the intended vessel service (see Part KE).

(a) For those services in which laminar discontinuities may be harmful, additional examination of materials prior to fabrication shall be specified by the User; for example, ultrasonic examination of plate in Section V, SA-435 and forgings in Section V, SA-388.

(b) State additional requirements such as nondestructive examinations, restricted chemistry, or heat treatments.

(c) The User shall state any nonmandatory or optional requirements of this Division that are considered to be mandatory for this vessel.

(d) The User shall state whether U.S. Customary or SI units are to be used in all certified documents, and on all marking and stamping required by this Division. The User shall also state if duplicate nameplates and certified
documents in a second language are required, and if there are any other special requirements for markings and their locations. See also KG-150 and KS-130.

(e) The User shall state requirements for seals and bolting for closures and covers (see KD-660).

(f) Specific additional requirements relating to pressure testing shall be listed in the User’s Design Specification, such as

1. fluid and temperature range
2. position of vessel
3. location, Manufacturer’s facility or on-site
4. cleaning and drying

(g) The User shall state in the User’s Design Specification what construction reports, records, or certifications, in addition to those listed in KS-320, the Manufacturer is required to provide to the User.

(h) See below.

1. The User shall state in the User’s Design Specification when the special requirements of Article KD-10 for vessels in high pressure hydrogen service shall be met.
2. The User shall ensure that the requirements of KD-1001 are met.

(i) The User shall state considerations for limiting the potential for unsatisfactory performance when subjected to service or test loads, if applicable. Examples of such considerations may be found in, but are not limited to, KD-231.2(b).

KG-311.15 Requirements for Engineers Who Sign and Certify a User’s Design Specification. Any Engineer who signs and certifies a User’s Design Specification shall meet one of the criteria shown in (a), (b), or (c) below and shall comply with the requirements of (d) and (e) below.

(a) A Registered Professional Engineer who is registered in one or more of the states of the United States of America or the provinces of Canada and experienced in pressure vessel design.

(b) An Engineer experienced in pressure vessel design who meets all required qualifications to perform engineering work and any supplemental requirements stipulated by the user and the licensing or registering authorities. The Engineer shall identify the location and the licensing or registering authorities under which he has received the authority to perform engineering work.

(c) An Engineer experienced in pressure vessel design who meets all required qualifications to perform engineering work and any supplemental requirements stipulated by the user. The Engineer shall be registered in the International Register of Professional Engineers of the Engineers Mobility Forum.

(d) The Engineer certifying the User’s Design Specification shall comply with the requirements of the location to practice engineering where that Specification is prepared unless the jurisdiction where the vessel will be installed has different certification requirements.

(e) When more than one Engineer certifies and signs the User’s Design Specification, the area of expertise shall be noted next to their signature under “areas of responsibilities” (e.g., design, metallurgy, pressure relief, fabrication, etc.). In addition, one of the Engineers signing the User’s Design Specification shall certify that all elements required by this Division are included in the Specification.

(f) An example of a typical User’s Design Specification Certification Form is shown in Form KG-311.15.

KG-311.16 Additional User’s Design Specification Requirements for Composite Reinforced Pressure Vessels (CRPV). The User shall state in the User’s Design Specification any provisions required for protection of the structural laminate layer from damage due to impact, ultraviolet radiation, or other environmental exposure; fire or abrasive conditions; and inservice degradation of the laminate for the life of the CRPV under the service conditions specified shall be stated in the User’s Design Specification (see KG-522).