Designation: D4506 – 13$^{\varepsilon 1}$

Standard Test Method for Determining In Situ Modulus of Deformation of Rock Mass Using Radial Jacking Test[1]

This standard is issued under the fixed designation D4506; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reapproval. A superscript epsilon (ε) indicates an editorial change since the last revision or reapproval.

ε[1] NOTE—Editorial corrections were made throughout in February 2014.

1. Scope*

1.1 This test method is used to determine the in situ modulus of deformation of rock mass by subjecting a test chamber of circular cross section to uniformly distributed radial loading; the consequent rock displacements are measured, from which elastic or deformation moduli may be calculated. The anisotropic deformability of the rock can also be measured and information on time-dependent deformation may be obtained.

1.2 This test method is based upon the procedures developed by the U.S. Bureau of Reclamation featuring long extensometers (**1**).[2] An alternative procedure is also available and is based on a reference bar (**2**). More information on radial jacking and its analysis is presented in References (**3-8**).

1.3 Application of the test results is beyond the scope of this test method, but may be an integral part of some testing programs.

1.4 *Units*—The values stated in inch-pound units are to be regarded as standard. The values given in parentheses are mathematical conversions to SI units that are provided for information only and are not considered standard. Reporting of test results in units other than inch-pound shall not be regarded as nonconformance with this test method.

1.4.1 The gravitational system of inch-pound units is used when dealing with inch-pound units. In this system, the pound (lbf) represents a unit of force (weight), while the unit for mass is slugs.

1.5 All observed and calculated values shall conform to the guidelines for significant digits and rounding established in Practice D6026.

1.5.1 The procedures used to specify how data are collected/recorded or calculated, in this standard are regarded as the industry standard. In addition, they are representative of the significant digits that generally should be retained. The procedures used do not consider material variation, purpose for obtaining the data, special purpose studies, or any considerations for the user's objectives; and it is common practice to increase or reduce significant digits of reported data to be commensurate with these considerations. It is beyond the scope of this standard to consider significant digits used in analytical methods for engineering design.

1.6 *This standard does not purport to address all of the safety concerns, if any, associated with its use. It is the responsibility of the user of this standard to establish appropriate safety and health practices and determine the applicability of regulatory limitations prior to use.*

2. Referenced Documents

2.1 *ASTM Standards:*[3]

D653 Terminology Relating to Soil, Rock, and Contained Fluids

D3740 Practice for Minimum Requirements for Agencies Engaged in Testing and/or Inspection of Soil and Rock as Used in Engineering Design and Construction

D4403 Practice for Extensometers Used in Rock

D6026 Practice for Using Significant Digits in Geotechnical Data

3. Terminology

3.1 *Definitions:*

3.1.1 For definitions of common technical terms in this standard, refer to Terminology D653.

3.2 *Definitions of Terms Specific to This Standard:*

3.2.1 *deformation*—the change in the diameter of the excavation in rock (test chamber).

[1] This test method is under the jurisdiction of ASTM Committee D18 on Soil and Rock and is the direct responsibility of Subcommittee D18.12 on Rock Mechanics.

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[2] The boldface numbers in parentheses refer to the list of references appended to this standard.

[3] For referenced ASTM standards, visit the ASTM website, www.astm.org, or contact ASTM Customer Service at service@astm.org. For *Annual Book of ASTM Standards* volume information, refer to the standard's Document Summary page on the ASTM website.

***A Summary of Changes section appears at the end of this standard**

4. Summary of Test Method

4.1 A circular test chamber is excavated and a uniformly distributed pressure is applied to the chamber surfaces by means of flat jacks positioned on a reaction frame. Rock deformation is measured by extensometers placed in boreholes perpendicular to the chamber surfaces. Pressure is measured with a standard hydraulic transducer. During the test, the pressure is cycled incrementally and deformation is read at each increment. The modulus is then calculated. The pressure is held constant and deformation is observed over time to determine time-dependent behavior.

5. Significance and Use

5.1 In this test method a volume of rock large enough to take into account the influence of discontinuities on the properties of the rock mass is loaded. This test method should be used when values are required which represent the true rock mass properties more closely than can be obtained through less expensive uniaxial jacking tests or other procedures.

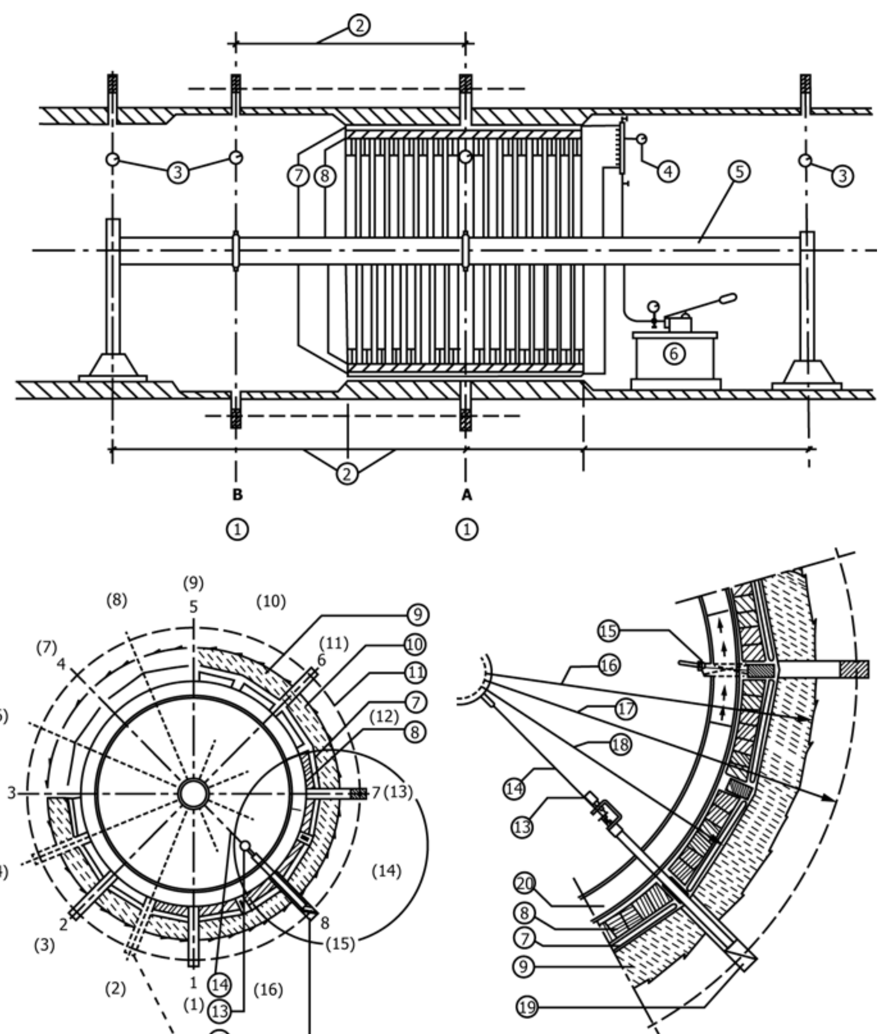
NOTE 1—The quality of the result produced by this standard is dependent on the competence of the personnel performing it, and the suitability of the equipment and facilities used. Agencies that meet the criteria of Practice D3740 are generally considered capable of competent and objective testing/sampling/inspection/etc. Users of this standard are cautioned that compliance with Practice D3740 does not in itself assure reliable results. Reliable results depend on many factors; Practice D3740 provides a means of evaluating some of those factors.

6. Apparatus

6.1 *Chamber Excavation Equipment*—Including drilling and "smooth wall" blasting equipment or mechanical excavation equipment capable of producing typically a 9-ft (3-m) diameter tunnel with a length about three times that dimension.

6.2 *Concreting Equipment*—Concreting materials and equipment for lining the tunnel, together with strips of weak jointing materials for segmenting the lining.

6.3 *Reaction Frame*—The reaction frame shall be comprised of steel rings of sufficient strength and rigidity to resist the force applied by flat jacks, as depicted in Fig. 1. For load



1. Measuring profile. 2. Distance equal to the length of active loading. 3. Control extensometer. 4. Pressure gauge. 5. Reference beam. 6. Hydraulic pump. 7. Flat jack. 8. Hardwood lagging. 9. Shotcrete. 10. Excavation diameter. 11. Measuring diameter. 12. Extensometer drillholes. 13. Dial gauge extensometer. 14. Steel rod. 15. Expansion wedges. 16. Excavation radius. 18. Inscribed Circle. 19. Rockbolt anchor. 20. Steel ring.

FIG. 1 Radial Jacking Test

application by flat jacks, the frame must be provided with smooth surfaces; hardwood planks are usually inserted between the flat jacks and the metal rings.

6.4 *Loading Equipment*—To apply a uniformly distributed radial pressure to the inner face of the concrete lining, including:

6.4.1 *Hydraulic Pump*—With all necessary hoses, connectors, and fluid, capable of applying the required pressure and of holding this pressure constant to within 5 % over a period of at least 24 h.

6.4.2 *Flat Jacks*—Used for load application (Fig. 1), and are of a practicable width and of a length equal at least to the diameter of the tunnel (9 ft (3 m)). The jacks should be designed to load the maximum of the full circumference of the lining with sufficient separation to allow displacement measurements, and should have a bursting pressure and travel consistent with the anticipated loads and displacements. Stainless steel flat jacks in effective contact with 90 % of the area are recommended, with the maximum pressure capacity twice the design pressure.

6.5 *Load Measuring Equipment*—Load measuring equipment shall consist of one or more hydraulic pressure gages or transducers of suitable range, capable of measuring the applied pressure with an accuracy better than ±2 %. Measurements are usually made by means of mechanical gages. Particular care is required to guarantee the reliability of electric transducers and recording equipment, when used.

6.6 *Displacement Measuring Equipment*—Displacement measuring equipment to monitor rock movements radial to the tunnel shall have an accuracy of at least ±0.0003 in. (0.1 mm) and resolution of at least 0.0001 in. (0.0025 mm). Multiple-position (six anchor points) extensometers in accordance with Practice D4403 should be used. The directions of measurement should be normal to the axis of the tunnel. Measurements of movement should be related to reference anchors rigidly secured in rock, well away from the influence of the loaded zone. The multiple-position extensometers should have the deepest anchor as a reference situated at least 3 test-chamber diameters from the chamber lining.

7. Verification

7.1 The compliance of all equipment and apparatus with the performance specifications in Section 6 shall be verified. The equipment and measurement systems should be included as part of the verification and documentation shall be accomplished in accordance with standard quality assurance procedures

8. Procedure

8.1 *Test Chamber:*

8.1.1 Select the test chamber location taking into consideration the rock conditions, particularly the orientation of the rock mass elements such as joints, bedding, and foliation in relation to the orientation of the proposed tunnel or opening for which results are required.

8.1.2 Excavate the test chamber by smooth (presplit) blasting to the required diameter of 9 ft (3 m), with a length equal to at least three diameters.

8.1.3 Record the geology of the chamber and specimens taken for index testing, as required. Core and log all instrumentation holes as follows:

8.1.3.1 *Cored Boreholes*—Drill the boreholes using diamond core techniques. Continuous core shall be obtained.

8.1.3.2 *Core Logged*—Completely log the recovered core, with emphasis on fractures and other mechanical nonhomogeneities.

8.1.4 Accurately mark out and drill the extensometer holes, making sure no interference between loading and measuring systems. Install six-point extensometers and check the equipment. Place two anchors deep beyond the tunnel influence, appropriately spacing the other four anchors as close to the surface of the tunnel as possible.

8.1.5 Assemble the reaction frame and loading equipment.

8.1.6 Line the chamber with concrete to fill the space between the frame and the rock.

8.2 *Loading:*

8.2.1 Perform the test with at least three loading and unloading cycles, a higher maximum pressure being applied at each cycle. Typically, the maximum pressure applied is 1000 psi (7 MPa), depending on expected design loads.

8.2.2 For each cycle, increase the pressure at an average rate of 100 psi/min (0.7 MPa/min) to the maximum for the cycle, taking not less than 10 intermediate sets of load-displacement readings in order to define a set of pressure-displacement curves (see Fig. 2). The automation of data recording is recommended.

8.2.3 On reaching the maximum pressure for the cycle, hold the pressure constant for 10 minutes. Complete each cycle by reducing the pressure to near zero at the same average rate, taking three additional sets of pressure-displacement readings.

8.2.4 For the final cycle, hold the maximum pressure constant for 24 h to evaluate creep. Complete the cycle by unloading in stages, taking readings of pressure and corresponding displacements similar to the loading cycle.

9. Calculation

9.1 Correct the applied load values to give an equivalent distributed pressure, p_1, on the test chamber lining, as follows:

$$p_1 = \frac{\sum b}{2 \cdot \pi \cdot r_1} \cdot p_m \quad (1)$$

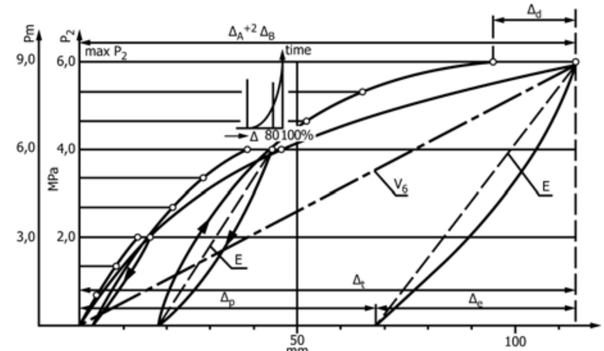


FIG. 2 Typical Graph of Applied Pressure Versus Displacement

where:

p_1 = distributed pressure on the lining at r_1, to the nearest 1 psi (0.007 MPa)
r_1 = radius, to the nearest 0.5 ft (0.15 m)
p_m = pressure in the flat jacks, to the nearest 1 psi (0.007 MPa)
b = flat jack width (see Fig. 3), to the nearest 0.5 ft (0.15 m)

9.1.1 Calculate the equivalent pressure P_2 at a "measuring radius" r_2 just beneath the lining; this radius being outside the zone of irregular stresses beneath the flat jacks and the lining and loose rock (see Fig. 3).

$$P_2 = \frac{r_1}{r_2} \cdot P_1 = \frac{\sum b}{2 \cdot \pi \cdot r_2} \cdot P_m \quad (2)$$

$$P_m \sum b = P_1 \cdot 2 \cdot r_1 \cdot \pi$$

$$P_1 = \frac{P_m \sum b}{2 \cdot \pi \cdot r_1}$$

$$P_2 = P_1 \frac{r_1}{r_2}$$

where:

P_2 = the equivalent pressure at measuring radius r_2, to the nearest 1 psi (0.007 MPa)
r_2 = measuring radius, to the nearest 0.5 ft (0.15 m)

9.2 Superposition is only strictly valid for elastic deformations but also gives a good approximation if the rock is moderately plastic in its behavior. Superposition of displacements for two fictitious loaded lengths is used to give the equivalent displacements for an "infinitely long test chamber." This superposition is made necessary by the comparatively short length of the test chamber in relation to its diameter.

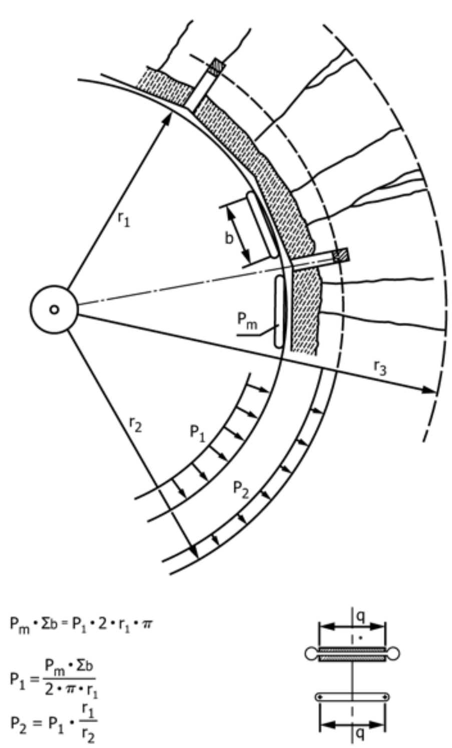


FIG. 3 Scheme of Loading Showing Symbols Used in the Calculations

9.3 Plot the result of the long duration test, Δ_d under maximum pressure, p_2, which is the maximum P_2 value, on the displacement graph (Fig. 4). Proportionally correct test data for each cycle to give the complete long-term pressure-displacement curve. The elastic component, Δ_e, and the plastic component, Δ_p, of the total deformation, Δ_t, are obtained from the deformation at the final unloading:

$$\Delta_t = \Delta_p + \Delta_e \ \text{(see Fig. 4)} \quad (3)$$

where:

Δ_e = elastic component
Δ_t = total deformation
Δ_p = plastic component

9.4 The elastic modulus, E, and the deformation modulus, D, are obtained from the pressure-displacement graph (Fig. 2) using the following formulae based on the theory of elasticity:

$$E = \frac{p_2 \cdot r_2}{\Delta_e} \cdot \frac{(1+\nu)}{\nu} \quad (4)$$

$$D = \frac{p_2 \cdot r_2}{\Delta_t} \cdot \frac{(1+\nu)}{\nu}$$

where:

p_2 = maximum test pressure, to the nearest 1 psi (0.007 MPa)
ν = estimated value for Poisson's Ratio
E = elastic modulus
D = deformation modulus

9.4.1 As an alternative to 9.4, the moduli of intact rock may be obtained, taking into account the effect of a fissured and loosened region, by using the following formulae:

$$E = \frac{p_2 \cdot r_2}{\Delta_e} \cdot \left(\frac{\nu + 1}{\nu} + ln \frac{r_3}{r_2} \right) \quad (5)$$

$$D = \frac{p_2 \cdot r_2}{\Delta_t} \cdot \left(\frac{\nu + 1}{\nu} + ln \frac{r_3}{r_2} \right)$$

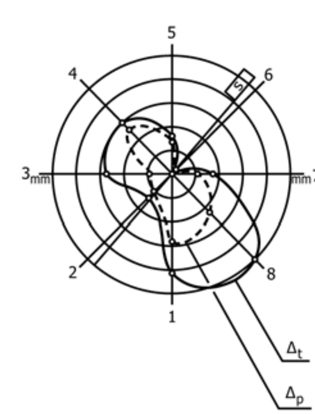


FIG. 4 Typical Graph Showing Total and Plastic Displacements as a Function of Direction Perpendicular to the Test Chamber Axis

where:

r_3 = radius to the limit of the assumed fissured and loosened zone, to the nearest 0.5 ft (0.15 m).

9.4.2 *Assumptions*—This solution is given for the case of a single measuring circle with extensometer anchors immediately behind the lining. The solution assumes linear-elastic behavior for the rock and is usually adequate in practice, although it is possible to analyze more complex test configurations (using, for example, a finite element analysis).

10. Report: Test Data Sheet(s)/Form(s)

10.1 The methodology used to specify how data are recorded on the test data sheet(s)/form(s) as given below, is covered in 1.5 and Practice D6026.

10.2 Record as a minimum the following general information (data):

10.2.1 The location and orientation of the test boreholes, a graphic presentation is recommended.

10.2.2 The reasons for selecting the test locations (**3**).

10.2.3 In general terms, the limitations of the testing program including areas of interest not covered by the testing program and the limitations of the data within the areas of application.

10.2.4 Describe the rock type/material macroscopically from both the field inspection and the core logs of the test boreholes.

10.2.5 Describe any structural features affecting the testing, as appropriate, include a listing of the types of data available on properties of the rock cores containing such property data as may aid in the interpretation of the test data. This type of data may include the rock quality designation (RQD) or laboratory tests of strength and deformation.

10.2.6 A detailed listing of the actual equipment used during the test, including the name, model number (if known), and basic specifications of each major piece of equipment.

10.2.7 List any deviations from the Procedure section.

10.2.8 Names of the personnel who performed the test(s). Include the dates the testing was performed.

10.3 Record as a minimum the following test data:

10.3.1 The distributed pressure p_1 on the lining at r_1, psi (MPa).

10.3.2 The equivalent pressure P_2 at a "measuring radius" r_2, psi (MPa).

10.3.3 The maximum pressure, p_2, psi (MPa).

10.3.4 Plot the result of the long duration test, Δd under maximum pressure, P_2, on the deformation graph.

10.3.5 List any variations in the requirements contained in this test method and the reason(s) for them. Indicate the effect the variation had upon the test results.

10.3.6 Discuss the degree to which the actual test site conditions conform to the assumptions contained in the data reduction equations and fully explain any factors or methods applied to the data to correct for a non-ideal situation.

10.3.7 The pressure range over which the modulus values were calculated. A summary table is recommended to present this data.

10.3.8 The average modulus values, ranges, and uncertainties. A summary table is recommended to present this data.

10.3.9 For individual results, list the extensometer number, the rock material/structure, and average modulus values for each location. A summary table is recommended to present this data.

10.3.10 A graphical representation of the typical pressure versus deformation curve for each rock material.

10.3.11 Include, as appropriate, the relationship between the modulus and applied stress, discussions of the modulus dependence on the geology, comparison with laboratory modulus values or the results of other in situ modulus tests, and comparison results to other rock types or previous studies.

10.4 Record as a minimum the following information regarding drawings:

10.4.1 A diagram giving the dimensions of the test equipment and instrumentation. Photographs of the test set-up should also be included.

10.4.2 Geological plans and sections of the test chamber showing the relative orientations of bedding, jointing, faulting, and any other features that may affect the test results, preferably with index test data to give further information on the mechanical characteristics of the rock tested.

10.4.3 Logs of geological and geotechnical data from the extensometer holes, including RQD, fracture spacing, and water pressure.

10.4.4 Transverse section of the test chamber showing the deformation resulting from the maximum pressure, as a function of the variation of extensometers (see Fig. 4). The orientations of significant geological fabrics should be shown on this figure for comparison with any anisotropy of test results.

10.4.5 The graphs showing deformation as a function of applied pressure (see Fig. 2) should be annotated to show the corresponding elastic and deformation moduli and data from which these were derived.

10.4.6 Any other results and data from other relevant deformability tests, both in situ and laboratory.

11. Precision and Bias

11.1 *Precision*—Test data on precision is not presented due to the nature of the rock materials tested by this test method. It is either not feasible or too costly at this time to have ten or more agencies participate in an in situ testing program at a given site. Subcommittee D18.12 is seeking any data from the users of this test method that might be used to make a limited statement on precision.

11.2 *Bias*—There is no accepted reference value for this test method; therefore, bias cannot be determined.

12. Keywords

12.1 discontinuities; in situ stress; loading tests; radial jacking test; rock; pressure

APPENDIX

(Nonmandatory Information)

X1. TEST FORM EXAMPLE

X1.1 This data sheet (Fig. X1.1) is provided as an example.

1	2	3	4	5	4 + 5	6	7	4 + 5 + 7	8	9
NR	time	p_2	Δ_A	Δ_B	$\Delta_A + \Delta_B$	Δ_d	Δ_d Corr.	Δ_t	Δ_e	Δ_p
1						—	—			
2						—	—			
3a							—			
3b							—			
3c										
4										
5										
6a							—			
6b							—			
6c										
7										
8										
9a										
9^{∞}							—			

$$E = \frac{p_2 \cdot r_2}{\Delta_e} \cdot \frac{\nu + 1}{\nu} = \_\_\_\_\_\_\_\_\_\_\_\_$$

$$V = \frac{p_2 \cdot r_2}{\Delta_t} \cdot \frac{\nu + 1}{\nu} = \_\_\_\_\_\_\_\_\_\_\_\_$$

FIG. X1.1 Suggested Layout for Test Data Sheet

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(3) Wohnlich, M., and Schade, D., "Analysis and Interpretation of Rock Parameters From a Radial Jack Test," *Rock Mechanics*, Vol 11, 1979, pp. 191–216.

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(7) Wallace, G. B., Slebir, E. J., and Anderson, F. A., "Radial Jacking Test for Arch Dams," *Proceedings, 10th U.S. Symposium on Rock Mechanics*, ASCE, New York, 1970, pp. 633–660.

(8) Lauffer, H., and Seeber, G., "Measurement of Rock Deformability with the Aid of the Radial Jack," *Proceedings, 1st International Congress on Rock Mechanics*, ISRM, Lisbon, 1966, Vol 2, pp. 347–356.

SUMMARY OF CHANGES

Committee D18 has identified the location of selected changes to this standard since the last issue (D4506 – 08) that may impact the use of this standard. (Approved Nov. 1, 2013.)

(1) Revised standard throughout.
(2) Added 1.4.1, 1.5, and 1.5.1.
(3) Rewrote Section 10.