ISO 6336-5: Strength and Quality of Materials

Comparison of AGMA 2001 and ISO 6336 ratings for four gear sets.

Don McVittie

This is the fourth and final article in a series exploring the new ISO 6336 gear rating standard and its methods of calculation. The opinions expressed herein are those of the author as an individual. They do not represent the opinions of any organization of which he is a member.

Gear rating standards are intended to provide a reliable method of comparing gear set capacities, when the same standard is used to calculate each example. It should not surprise us that the same gear set has a different rated capacity when calculated by the ISO and AGMA standards. We should expect, however, that the ratio between ISO rated capacity and AGMA rated capacity be approximately the same for different gear sets. This article examines the calculated ratings of four gear sets and explores some possible causes for differences. Some differences are due to allowable material stress numbers and some are due to other influence factors. Tables provide specifics of the four gear sets and the influence factors according to each standard.

Classification of Materials

ISO 6336-5 contains data for a wide variety of cast and wrought ferrous gear materials with different heat treatment conditions. The material types are shown in Fig. 1, with the abbreviations assigned to each type.

St = Steel (σ_B < 800 N/mm^2)*
V = Through-hardening steel, through-hardened ($\sigma_B \geq$ 800 N/mm^2)*
GG = Grey cast iron
GGG (perl., bai., ferr.) = Nodular cast iron (perlitic, bainitic, ferritic structure)
GTS (perl.) = Black malleable cast iron (perlitic structure)
Eh = Case-hardening steel, case hardened
IF = Steel and GGG, flame or induction hardened
NT (nitr.) = Nitriding steel, nitrided
NV (nitr.) = Through-hardening and case-hardening steel, nitrided
NV (nitrocar.) = Through-hardening and case-hardening steel, nitrocarburized
*σ_B is ultimate tensile strength, approximately 3.4 • BHN, N/mm^2

Fig. 1 — Material Types in ISO 6336-5.

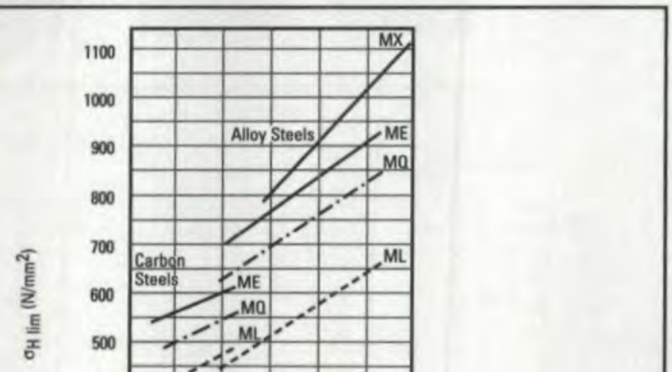

Fig. 2 — Through hardening steels: Allowable stress numbers (contact).

Note that through-hardening steels softer than approximately 235 BHN are classified as carbon steels (St) rather than as through-hardened alloy steels (V) with a reduction in allowable stress numbers. Carburizing steels are subdivided into three subclasses, depending on hardenability and minimum core hardness. Nitriding steels are also subdivided into several subclasses, depending on alloy content.

Each material type is subdivided into quality grades according to the cleanliness and processing criteria established in section 6 of the standard.

- Grade ML stands for the minimum requirement, similar to AGMA grade 1.
- Grade MQ represents requirements which can be met by experienced manufacturers at moderate cost, similar to AGMA grade 2. MQ is also the default material grade for industrial gears.
- Grade ME represents requirements which must be realized when higher allowable stresses are desirable, similar to AGMA grade 3.
- Grade MX is a special grade of through-hardened steel, with hardenability selected for the critical section size.

Although ML, MQ and ME requirements are listed for all material types, not all of these combinations are readily available in the market. An effort is being made to reduce the number of grades for the next edition of ISO 6336-5.

Allowable Stress Numbers

The ISO 6336-5 standard describes the methods used to derive allowable stress numbers from full scale gear tests (method A), reference test gears or test specimens. The stress numbers represent a survival rate of 99%, as in the AGMA standards. At present, ISO 6336 does not offer a specific way to calculate ratings for other survival rates.

Allowable stress numbers for recognized gear materials are presented in graphical form. Figures 2 and 3 are examples of those graphs.

The allowable stress numbers for pitting and bending are plotted against surface hardness, which is expressed in either Brinell or Vickers units. HB is used for softer materials, HV 10 (10 kg load) is used for most through-hardened materials and HV 1 (1 kg load) is used where appropriate for surface hardened materials. The allowable stress numbers for grade MQ are comparable to those for AGMA grade 2, except for the pitting strength of through-hardened alloy steels. Many experienced manufacturers of through-hardened gears will find that their products can meet the requirements of grade MX, which has allowable contact stress numbers comparable to AGMA grade 2. Figure 2 shows the higher allowable contact stress numbers permitted for the MX grade of through-hardened alloy steels, compared to ML, MQ and ME.

Requirements for Material Quality and Heat Treatment

A series of tables defines the metallurgical requirements for each grade of each material class. There is good general agreement between the ISO and AGMA requirements for similar materials and allowable stress numbers, but ISO metallurgical quality standards rather than ASTM are the reference documents for ISO standards. Your steel supplier and heat treaters will need to know the ISO standards to be sure that their work complies with the detailed requirements.

There are a few places where the details of the measurement methods and specifications differ. For example, the specified point to measure core hardness in a finished tooth per ISO 6336 is one module below the surface on a line perpendicular to the 30° tangent to the root fillet, rather than on the center of the tooth on the root diameter as in AGMA (Fig. 4). These differences don't affect the engineer making rating calculations, but they could be of concern in heat treatment control and certification.

The ISO standard recognizes *process control test bars*, which may be any size, to monitor the consistency of the heat treatment process and *representative test bars*, which are large enough to represent the quench rate of the finished part. The microstructure of the *representative test bars* may be considered equivalent to that of the finished part for quality assurance. Several informative annexes are provided, including a conversion table between ultimate tensile strength, Vickers, Brinell and Rockwell hardness values.

The following calculated examples represent actual gear sets for which performance is known from either back-to-back testing or field experience. In each case, a few geometrical values have been changed to make the example generic.

ISO does not directly calculate an allowable power for a gear set, nor does AGMA calculate a safety factor. In order to make the comparison tables, the "ISO allowable power" was calculated from the safety factor. The calculation was made with the values of $K_{H\beta}$ and K_v obtained at nominal load, disregarding the change in those factors due to load dependence. The "AGMA safety factors" were calculated by comparing allowable stress numbers to calculated stress numbers, as in ISO.

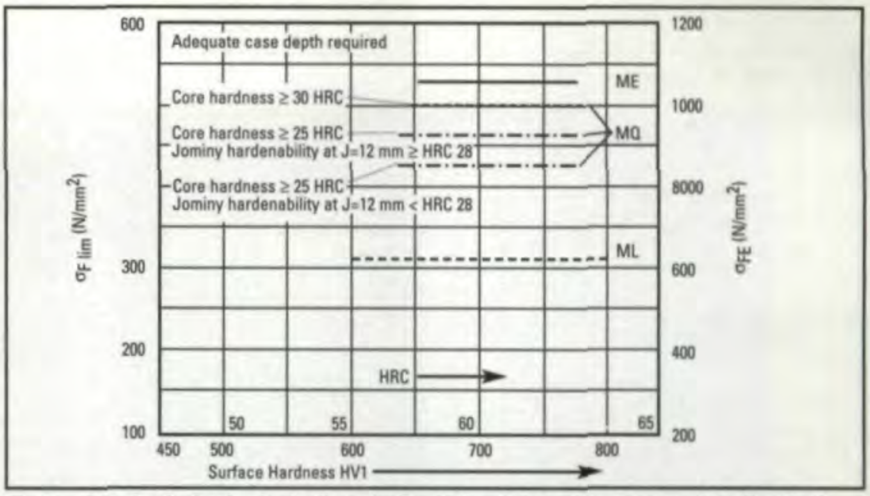

Fig. 3 — Case hardening (carburized) steels: Nominal and allowable stress numbers (bending).

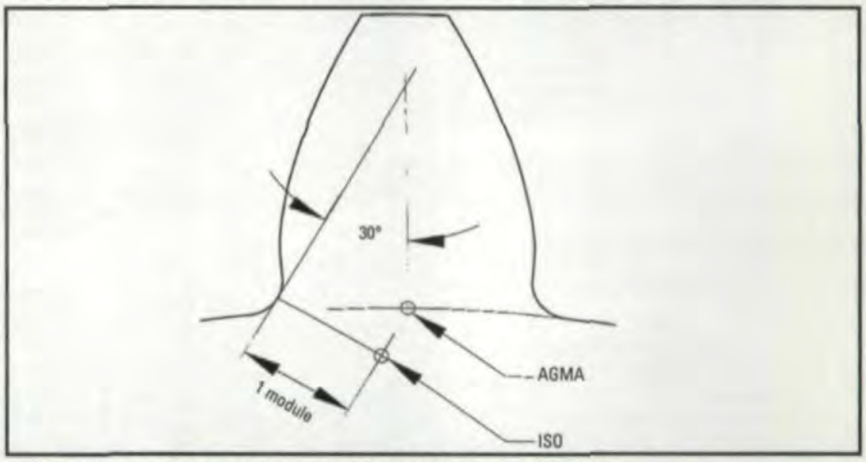

Fig. 4 — Core hardness measurement point in ISO 6336 vs. AGMA 2001.

Comparison ISO v. AGMA ratings for four example gear sets:

Example Number	1	2	3	4
Application	Gear Motor, HS	Catalog reducer, LS	Wind turbine, LS	Rolling mill final red.
Center Distance, mm (in)	39.32 (1.548)	266.7 (10.500)	630 (24.803)	2378.03 (93.623)
Pinion speed, rpm	1750	340	180	175
Input power, KW (HP)	0.373 (0.50)	224 (300)	300 (402)	1475 (1975)
Application factor	1.00	1.00	1.75	2.50
ISO Rated Power, KW	0.31	256	421	1538
AGMA Rated Power, KW	0.78	260	305	1680
ISO pitting safety factor	0.91	1.07	1.23	1.02
AGMA pitting safety factor	1.97	1.08	1.09	1.07
ISO bending safety factor	2.41	1.71	1.40	2.01
AGMA bending safety factor	2.09	1.25	1.02	1.23
Pinion material	Induct. hard.	Carburized	Carburized	
Through hardened				
Gear Material	Induct. hard.	Carburized	Carburized	Through hardened
Tooth form	28 DP helical	6 Mod. helical	7 Mod. helical	1.5 DP Herringbone
Notes	Catalog rating >10000 units in field	Catalog rating Lab test confirmed	Miner's rule equivalent application factor	25 year service life

Example 1: Small gear motor speed reducer. Thousands of these induction hardened gear sets are in service, driven by 1/2 horsepower (0.373 KW) 1750 rpm AC induction motors. Since this is a catalog rating, the application factor is set to 1.0. The ISO 6336 pitting safety factor is less than 1.0, indicating a high risk of pitting failure at this power. The AGMA pitting safety factor is almost 2. The principal difference is in the face load distribution factor $K_{H\beta}$, which is 2.083 according to ISO method C and 1.16 according to AGMA 2001. This is probably a good place to use method A (full scale, full load testing) or method B (measurement of misalignment under load) to determine the appropriate value. There is a significant difference between the ISO and AGMA allowable stress numbers for spin induction

Don McVittie

is one of Gear Technology*'s technical editors. He is president of Gear Engineers, Inc., Seattle, WA and a former president of AGMA. McVittie is a licensed professional engineer in the state of Washington and has been involved with gear standards development for more than 25 years.*

GEAR ENGINEERS, INC.
Comparison ISO v. AGMA ratings for four example gear sets: 14–Oct–1998

Example Number	1		2		3		4	
	Gear Motor		Catalog reducer		Wind Turbine		Rolling Mill	
Standard	ISO	AGMA	ISO	AGMA	ISO	AGMA	ISO	AGMA
INPUT DATA:								
Center distance	39.324	1.5482	266.7	10.5	630.001	24.8032	2378.03	93.6232
Pinion No. Teeth	13	13	17	17	25	25	24	24
Gear No. Teeth	68	68	69	69	151	151	210	210
Module/Dia. Pitch	*0.9071*	*28.00*	*6*	*4.23*	*7*	*3.63*	*17.602*	*1.44*
Pinion face width	16.00	0.6299	120.65	4.75	204.00	8.0315	914.40	36
Gear face width	12.70	0.5	120.65	4.75	204.00	8.0315	914.40	36
Double helical	No	No	No	No	No	No	Yes	Yes
Gap between helices	0	0	0	0	0	0	15.875	0.63
X pinion	0.4697	0.4697	0.5187	0.5187	0.25	0.25	0.462	0.462
X gear	0.5987	0.5987	0.4614	0.4614	-0.2159	-0.2159	-0.462	-0.462
Normal Ref. pressure angle	20	20	20	20	25	25	17.495	17.495
Ref. helix angle	17	17	9	9	12	12	30	30
Pinion tip dia	14.94	0.588	121.03	4.765	196.41	7.7327	536.44	21.1197
Gear tip dia.	67.34	2.651	436.35	17.179	1091.59	42.976	4283.46	168.64
Pinion constr: Solid (1), Rim (2)	1		1		1		1	
Pinion web thickness			0			0	0	0
Pinion rim ID	0	0		0		0		
Pinion no. of webs	0		0		0	0		
Gear constr: Solid (1), Rim (2)	1		1		2		2	
Gear web thickness					65		50	
Gear rim ID					1011.6		4064	
Gear no. of webs	0		0		1		2	
Accuracy grade, pinion	6	11	6	11	6	11	8	9
Accuracy grade, gear	7	10	6	11	7	10	8	9
Flank roughness, pinion, mu-m	*1.6*		*0.406*		*0.4*		*3.175*	
Flank roughness, gear, mu-m	1.6		0.406		0.4		3.175	
Root fillet roughness, pinion, mu-m	2.28		3		2		6.2	
Root fillet roughness, gear, mu-m	2.28		3		2		6.175	
Crowning configuration	2		2		2		0	
Bearing arrangement	3		5		3		1	
Location of contact	7		7		7		7	
Initial misalignment	0		0		0		0	
Input face load distr. factor	0		0		0		0	
Finish stock allow. pinion	0	0	0.178	0.0297	0.224	0.032	0	0
Finish stock allow. gear	0	0	0.178	0.0297	0.224	0.032	0	0
Design tip relief	0		0		0.035		0	
Pinion tool addendum factor	1.25	1.25	1.40	1.40	1.30	1.30	1.15	1.15
Gear tool addendum factor	1.25	1.25	1.40	1.40	1.30	1.30	1.15	1.15
Pinion tool protuberance	0	0	0.2977	0.0496	0.294	0.042	0	0
Gear tool protuberance	0	0	0.2977	0.0496	0.294	0.042	0	0
Pinion tool tip radius	0.30	0.30	0.40	0.40	0.25	0.25	0.20	0.20
Gear tool tip radius	0.30	0.30	0.40	0.40	0.25	0.25	0.20	0.20
Pinion material yield strength							690	
Gear material yield strength							690	
Hardness scale, pinion	HRC	HB	HRC	HRC	HRC	HRC	HB	HB
Hardness scale, gear	*HRC*	*HB*	*HRC*	*HRC*	*HRC*	*HRC*	*HB*	*HB*
Pinion surface hardness	56	578	58	58	58	58	284	284
Gear surface hardness	54	548	58	58	58	58	266	266
Pinion material	IF	Ind (B)	Eh	Carb.	Eh	Carb.	V	TH
Pinion material subclass	1		2		1		1	
Gear material	IF	Ind (B)	Eh	Carb.	Eh	Carb.	V	TH
Gear material subclass	1		2		1		1	
Pinion material grade	MQ	2	MQ	2	MQ	2	MX	2
Gear materilal grade	MQ	2	MQ	2	MQ	2	MX	2
Bearing span	220.78	8.692	288.54	11.36	640.00	25.197	1317.60	51.874
Pinion offset	39.85	1.569	51.82	2.04	60.00	2.362	0.00	0
Pinion shaft outside diameter	20.64	0.8125	88.90	3.5	150.00	5.906	330.00	12.992
Pinion shaft inside diameter	0	0	0	0	0	0	0	0
Pinion idler?	No	No	No	No	No	No	No	No
Gear idler?	No	No	No	No	No	No	No	No
Application factor	1	1	1	1	1.75	1.75	2.5	2.5
Pinion Torque, Nm	2.0353		6274		15950		80493	
Pinion speed	1750	1750	340.48	340.48	180	180	175	175
Input power, KW	0.373	0.373	224	224	300.628	300.638	1475	1475
Minimum safety factor, durability	1		1		1		1	
Minimum safety factor, bending	1.50		1.00		1.20		1.20	
Pitting life required, hours	10000	10000	10000	10000	100000	100000	100000	100000
Bending life required, hours	10000	10000	10000	10000	100000	100000	100000	100000
Pitting permitted, pinion?	No		No		No		No	
Pitting permitted, gear?	No		No		No		No	
Input pitting life factor, pinion	0		0		0		0	
Input pitting life factor, gear	0		0		0		0	
Input bending life factor, pinion	0		0		0		0	
Input bending life factor, gear	0		0		0		0	
Input pitting life factor for 10^10, pinion	1.00		1.00		0.85		0.85	
Input pitting life factor for 10^10, gear	1.00		1.00		0.85		0.85	
Input bendng life factor for 10^10, pinion	*1.00*		*1.00*		*0.85*		*0.85*	
Input bendng life factor for 10^10, gear	1.00		1.00		0.85		0.85	
Kinematic oil viscosity at 40 C	320		220		320		560	
CALCULATED RESULTS, SI UNITS:								
Pitting safety factor, pinion	0.92	1.97	1.07	1.08	1.23	1.09	1.02	1.07
Pitting safety factor, gear	0.91	2.04	1.07	1.11	1.30	1.14	1.04	1.07
Bending safety factor, pinion	2.97	2.09	1.71	1.25	1.40	1.02	2.15	1.32
Bending safety factor, gear	2.41	2.20	1.75	1.27	1.42	1.07	2.01	1.23
Allowable power, KW	0.31	0.78	256.11	259.83	421.48	305.44	1538	1680
Pinion allowable power, pitting	0.32	1.45	256.11	259.83	456.30	359.11	1538	1686
Gear allowable power, pitting	0.31	1.56	256.11	277.12	509.63	390.08	1605	1680
Pinion allowable power, bending	1.11	0.78	383.19	279.13	421.48	305.44	3176	1944
Gear allowable power, bending	0.90	0.82	391.24	284.12	425.69	321.80	2968	1810
Face load distribution factor	2.083	1.16	1.266	1.2209	1.084	1.273	1.684	1.84
Dynamic factor	1.036	1.068	1.005	1.049	1.005	1.081	1.025	1.185
Pitting stress at input power	1149	614	1419	1344	1173	1275	738	756
Allowable pitting stress, pinion	1062	1209	1518	1448	1445	1393	753	808
Allowable pitting stress, gear	1043	1255	1518	1496	1527	1452	769	806
Pinion bending stress at input power	244	68	512	374	618	445	243	223
Allowable bending stress, pinion	*482*	*142*	*877*	*465*	*722*	*452*	*436*	*294*
Gear bending stress at input power	302	67	503	376	636	436	264	239
Allowable bending stress, gear	485	146	877	477	751	467	443	293
Life factor, pinion pitting	1	0.899	1	0.933	0.91	0.898	0.911	0.899
Life factor, gear pitting	1	0.933	1	0.964	0.962	0.936	0.974	0.944
Life factor, pinion bending	1	0.937	1	0.964	0.889	0.936	0.889	0.937
Life factor, gear bending	1	0.965	1	0.989	0.921	0.967	0.929	0.974

hardened materials, which also affects the rated capacity of this gear set.

Example 2: Standard catalog speed reducer. This is the low speed mesh of a carburized and ground double reduction catalog reducer similar to that manufactured by several large companies in the international market. Gears of this type rate almost identically under AGMA and ISO standards. Many full scale laboratory tests have confirmed these ratings. Since this is a catalog rating, the application factor is set to 1.0.

Example 3: Wind turbine speed increaser. The wind turbine example is a carburized and ground speed increasing drive subject to extremely variable loading with high overloads from wind gusts and the nature of the driven generator. An application factor was chosen for this drive based on a Miner's rule analysis of the effects of the load spectrum and applied to compare the ISO and AGMA ratings of this gear mesh. The ISO method calculates about a 14% higher pitting stress safety factor (30% higher power rating) than AGMA, primarily due to the difference in $K_{H\beta}$. The AGMA rated capacity of this drive has been confirmed by testing and field experience. It should be noted that the calculation of capacity by Miner's rule is more complicated under the ISO standard, since the values of load distribution and dynamic factors are load dependent, requiring a recalculation of all factors for each step of the load spectrum.

Example 4: Large through hardened rolling mill drive. The mill drive example is from a double helical (herringbone) rolling mill stand which survived 15 years at 85% of the rated power, followed by ten years at full rated power. It was replaced due to wear and pitting of the tooth profiles. The ISO pitting safety factor is slightly lower than the AGMA value due to differences in the allowable stress number. In this example the ISO load distribution factor is lower than AGMA, which partially offsets the difference in allowable stress numbers.

Figure 5 compares the minimum calculated pitting and bending stress safety factors for the four examples. The examples are characterized by center distance in the figure, but it should not be implied that center distance alone explains the differences between the ISO and AGMA safety factors for these four very different gear sets.

What Causes the Differences in Calculated Capacity in These Examples?

The tabulated results show that the calculated pitting capacities are very similar, with differences being mostly dependent on the evaluation of $K_{H\beta}$, the face load distribution factor. The difference in the dynamic factor also has an effect, particularly in very large gears.

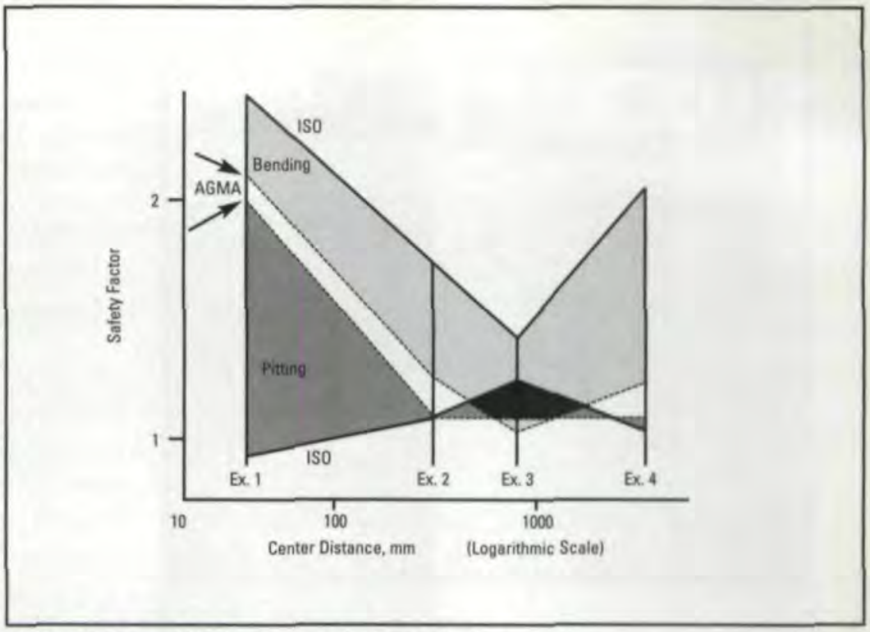

Fig. 5 — Pitting and bending stress safety factors for four examples.

In comparing ISO to AGMA, remember that the calculated ISO bending stress numbers include a stress concentration factor Y_S, which ranges from approximately 1.4 to 2.2 depending on tooth form and fillet roughness. It has a value of $Y_{ST} = 2.0$ for the test gears used to develop the allowable stress numbers for the materials. In short, both the ISO calculated root stress numbers and the ISO allowable stress numbers are about twice the AGMA numbers.

The calculated bending capacities according to ISO are generally much higher than the capacitiesaccording to AGMA. It appears from these examples that a minimum ISO bending safety factor of 1.3 would be required to have the same conservatism as the AGMA rating practice. It should also be clear from the examples that there is not a simple relationship between the ISO and AGMA rating results. In order to understand how your gears will rate under ISO 6336 you will have to go through the calculations case by case and compare the results.

You Can Have a Voice in Future Revisions of the ISO Gear Standards.

If you find errors or disagree with the ISO standard's calculation of the capacity of a specific class of gears, you can work through the ANSI Technical Advisory Group (TAG) to ISO Technical Committee (TC) 60, sponsored by AGMA, to suggest changes to the standard. Those suggestions should be well supported by calculations and test results to demonstrate the need for the changes proposed. The ANSI TAG meets regularly to establish the U.S. position on ISO standards. If there is a U.S. consensus for your proposal, it will become a U.S. proposal to ISO TC60, which is responsible for changes and updates to the standard. TC60 is already working on the next revision of ISO 6336, which is due to be completed in 2001. ○