Hindawi Publishing Corporation
Advances in Tribology
Volume 2013, Article ID 521086, 8 pages
http://dx.doi.org/10.1155/2013/521086

Review Article

The Head-Disk Interface Roadmap to an Areal Density of 4 Tbit/in^2

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Received 10 December 2012; Accepted 12 February 2013

Academic Editor: Tom Karis

This paper reviews the state of the head-disk interface (HDI) technology, and more particularly the head-medium spacing (HMS), for today's and future hard-disk drives. Current storage areal density on a disk surface is fast approaching the one terabit per square inch mark, although the compound annual growth rate has reduced considerably from ~100%/annum in the late 1990s to 20–30% today. This rate is now lower than the historical, Moore's law equivalent of ~40%/annum. A necessary enabler to a high areal density is the HMS, or the distance from the bottom of the read sensor on the flying head to the top of the magnetic medium on the rotating disk. This paper describes the various components of the HMS and various scenarios and challenges on how to achieve a goal of 4.0–4.5 nm for the 4 Tbit/in^2 density point. Special considerations will also be given to the implication of disruptive technologies such as sealing the drive in an inert atmosphere and novel recording schemes such as bit patterned media and heat assisted magnetic recording.

1. Introduction

As the areal density of commercial hard disk drives is quickly approaching the terabit per square inch milestone [1–5] (Figure 1), the need to improve the reliability of the head-disk interface (HDI) and to further decrease the head-medium spacing (HMS) is becoming eversmore critical [3, 6, 7]. Low HMS is a necessary enabler to good writability as well as strong read-back signal integrity [8, 9]. It is estimated that the HMS will soon need to cross the 7 nm mark in order to reach this terabit per square inch density point [2, 6]. It is remarkable to realize that the error rate of the stored digital signal that is being read back improves approximately by about 2x for every 0.3–0.5 nanometer of decreased HMS. In addition to relentless demand for novel, ultrathin protecting films of overcoat and lubricant, and subnanometer air gap between the disk and the head, alternative recording technologies presently being contemplated involve heating the disk to over 500°C (heat-assisted magnetic recording or HAMR) [10–12] and/or physically isolating magnetic bits on small islands of sub-30 nm in physical dimensions (bit-patterned recording or BPR) [13–16].

In this paper, the roadmap to an areal density of 4 terabits per square inches will be discussed. Particular emphasis will be given to the various spacing components that comprise the HMS budgetand their physical limits. The various implications of recording technologies incorporating HAMR and/or BPR will also be addressed.

2. Historical Perspective

Hard drive technology has constantly evolved to achieve consistent areal density growth. As one technology such as longitudinal recording has reached its limit, another such as perpendicular recording has taken over [18]. Along with advances in heads, media, signal processing, and servo technology, areal density growth is sustained through improvements in the head-disk interface (HDI). Head-media spacing (HMS) is the most important HDI parameter related to areal density growth [6]. Continued developments in the tribological design of disk drives have maintained the reliability of the head/disk interface despite decreased spacing.

Analysis of long-term trends shows that HMS has steadily declined over time (Figure 2). The historical trends indicate

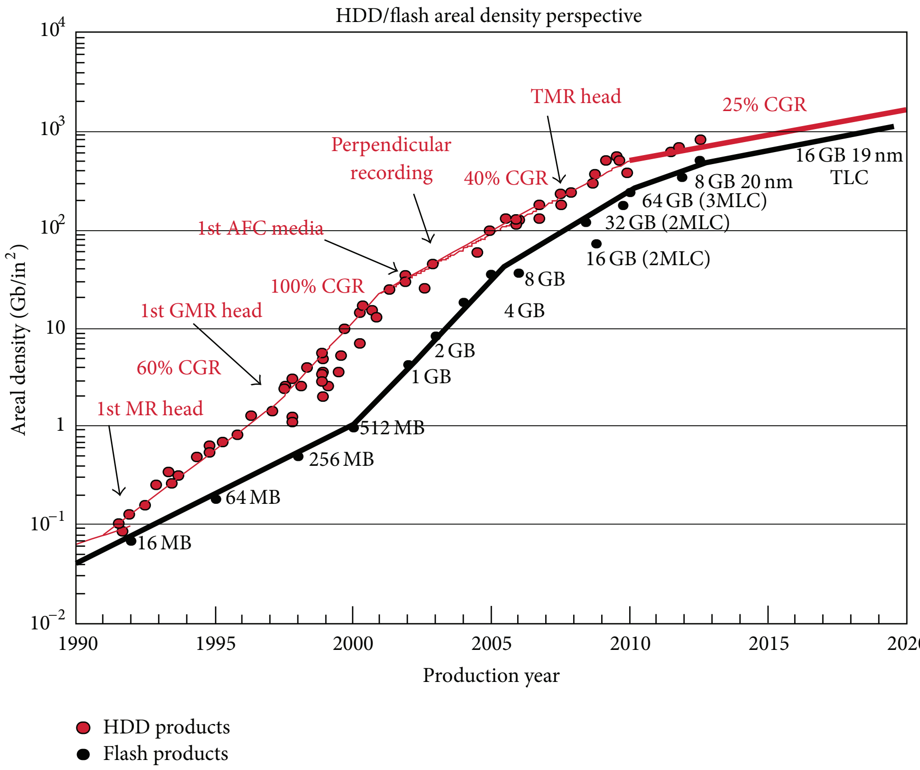

Figure 1: Areal density evolution of HDD and flash memory. After Grochowski [17], with permission.

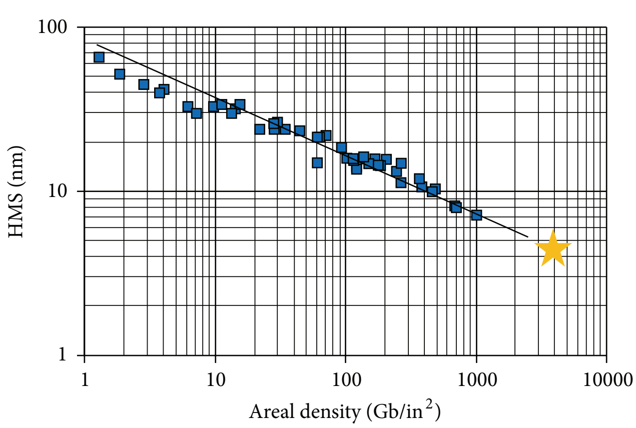

Figure 2: Historical variations of HMS versus areal density from [6]. The yellow star is an extrapolation to 4 Tb/in^2.

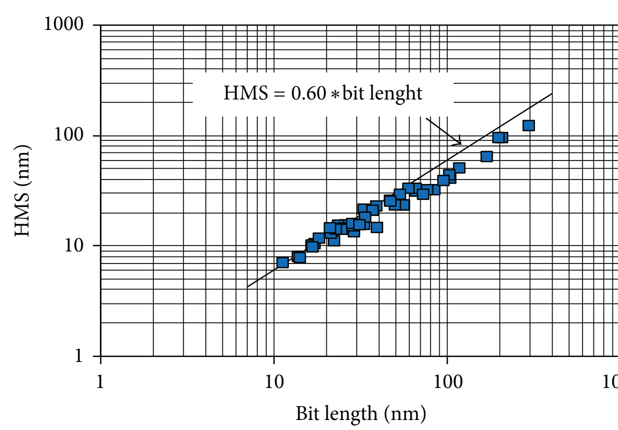

Figure 3: Historical variations of HMS versus bit length from [6].

that the HMS of recent products is ~60% of bit length (Figure 3) [6]. The HMS for recording demonstrations has been typically more aggressive, at ~50% of bit length.

Research consortia such as the Information Storage Industry Consortium (INSIC—https://www.insic.com/), Storage Research Consortium (SRC—http://www.srcjp.gr.jp/), and the Advanced Storage Technology Consortium (ASTC—http://www.idema.org/?page_id=3193) have included collaborations on HDI technology development. For each areal density, the HMS target has typically been set by the Recording Subsystem (RSS) groups. The past and current HMS trends for the different consortia are shown in Figure 4. The HMS trends have typically followed the overall trends of Figures 2 and 3 fairly well. For the HMS roadmaps released in 2003–2010, the INSIC trend tended to be lower than for SRC. For the current update (2012), the ASTC trend is higher than SRC.

For ASTC the main areal density targets are 2 Tb/in^2 and 4 Tb/in^2, with scheduled product introductions of 2016 and 2020, respectively. The current HMS targets for these two density points is ~5-6 and 4-5 nm, respectively, that is, less aggressive than those for INSIC. The 4 Tb/in^2 HMS goal will be discussed in more details in Section 4.

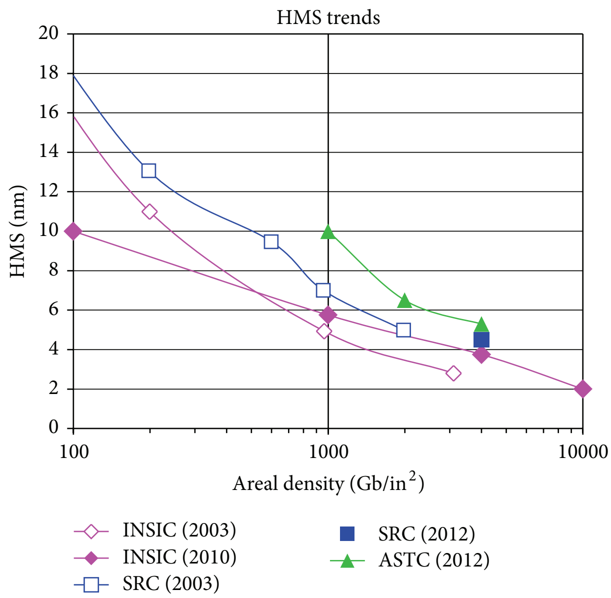

FIGURE 4: HMS trends of industry research consortia.

3. Definition of the Head-Media Spacing Components

As the capacity and performance of disk drives has improved, the mechanical interface has evolved. The spacing between the head and the media has steadily decreased to achieve the rapid improvements in areal density. Figure 5 is a diagram of head-media spacing (HMS). The HMS is comprised of the fly height and coatings (head and disk overcoats, disk lubricant).

In the diagram of Figure 5(b), the surfaces are assumed to be perfectly smooth—they do not include factors such as surface topography and variability of the fly height. The fly height denotes the spacing between the centerline surfaces of the head and disk. The clearance denotes the spacing between the close points of the surfaces. The distinction between fly height and clearance is depicted in Figure 6.

Below are some definitions of terms commonly used by the HDI/tribology community.

(1) Head-media spacing (HMS): the spacing between the top of the magnetic layer and the surface of the transducer.

(2) Flying clearance: difference or margin in fly height between nominal operation and contact between the head and disk.

(3) Glide avalanche/touchdown height (TDH): the lowest slider flying height above the mean roughness level without significant slider-disk contact

(4) Flying height = flying clearance + touchdown height

(5) Media lubricant thickness: the average thickness of the lubricant, assumed to be on top of the media overcoat

(6) Media cvercoat thickness: the average thickness of the media overcoat, assumed to follow the topography of the underlying surface

(7) Head overcoat: head adhesion layer (e.g., silicon) + diamond-like carbon (DLC)

$$\begin{aligned}\text{HMS} &= \text{head overcoat} + \text{TDH} + \text{clearance} \\ &\quad + \text{media lubricant} + \text{media overcoat}\end{aligned} \tag{1}$$

For current hard drives, HMS reductions have been achieved mostly through reductions in the clearance and disk and head overcoats. While this trend will continue for the immediate future, additional HMS reductions will soon require notraditional HDI designs in order to meet the demanding recording requirements for areal densities beyond $1\,\text{Tb/in}^2$.

In older drive designs, the air bearing design and passive topography of the slider determined the fly height and clearance of the transducer. In newer drive designs, the fly height is actively controlled by a signal that changes the shape of the slider. The most common method used for this control is to embed an electrical resistive heater in the slider that will cause the transducer area to protrude closer to the disk, as is shown in Figure 6 [19–21]. At some point the interface may need to be designed to withstand intermittent or continuous contact [22–27].

Current products have HMS on the order of 10 nm or slightly below [6]. For the $1\,\text{Tb/in}^2$ products under development, a Hi-Lo range bracket can be defined, since this areal density point is no longer precompetitive. For beyond $1\,\text{Tb/in}^2$, achievable and stretch values were estimated. The technological development required to achieve the targets will be discussed in Section 4. The assessment indicated that there is promise for achieving 4–6 nm HMS in the long term. While advancements in HDI design could enable significant reduction in HMS, new recording schemes could add to the challenge due to new sources of HMS loss: heat assisted magnetic recording (HAMR) will experience effects of high temperature at the interface [28–30], and bit-patterned magnetic recording (BPR) could have issues with added disk topography that would add to the touchdown height [31–34].

4. ASTC HDI Roadmap to $4\,\text{Tb/in}^2$ and Major Research Challenges

As shown in Figure 2, a good estimation of the HMS is ~60% of the length of the bit, and some rationale for this was recently proposed [6]. This offers a convenient way to project future HMS values, as the following simple equations can be derived. If one defines areal density (AD) in bits per square inch as the product of the linear density in bit per inch (BPI) and track density (TPI), AD = BPI · TPI. Furthermore, the bit aspect ratio BAR is usually defined as BAR = BPI/TPI; hence, the bit length (BL), in inches, can be expressed as

$$\text{BL} = (\text{AD} \cdot \text{BAR})^{-1/2}. \tag{2}$$

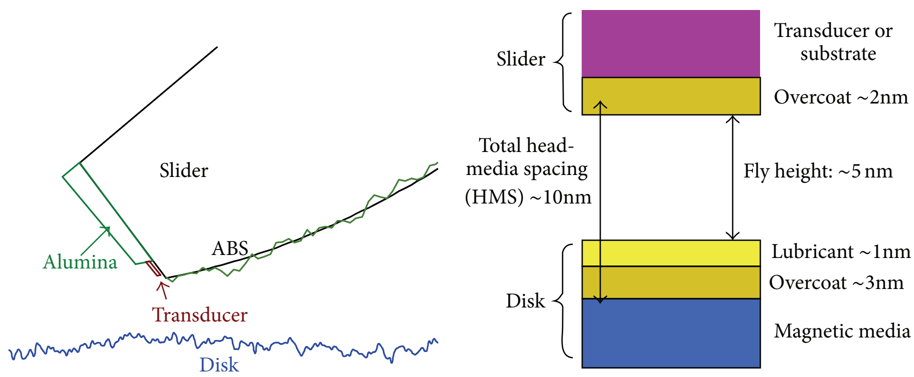

FIGURE 5: Components of head-disk spacing: (a) schematic of trailing end of head as it flies over disk. (b) Idealized HMS stacks up.

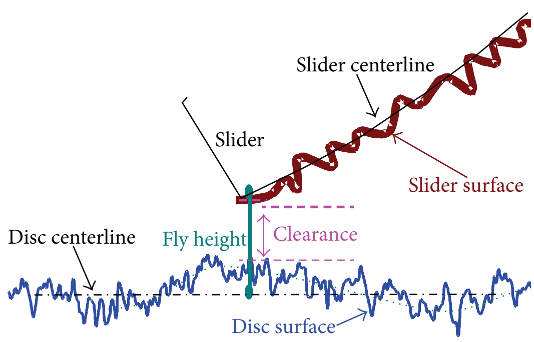

FIGURE 6: Parameters related to head-disk clearance and fly height.

TABLE 1: Estimated HMS (nm) values as a function of AD and BAR.

	BAR			
AD (Tb/in^2)	3.0	3.5	4.0	4.5
2	6.2	5.8	5.4	5.1
4	4.4	4.1	3.8	3.6

With the HMS approximation of 60% of BL, we now have a very convenient expression linking HMS (in nanometer) to AD (in Tb/in^2), for a given BAR:

$$\text{HMS (nm)} \approx 15 \cdot (\text{AD} \cdot \text{BAR})^{-1/2}. \quad (3)$$

Numerical HMS values based on (3) are reproduced in Table 1 below.

As shown in Table 1, achieving a 4 Tb/in^2 areal density will require an HMS in the vicinity of ~4.4 nm, assuming a bit aspect ratio (BAR) of 3. Table 2 offers two scenarios for the HMS breakdown into its various components. In the table, the 2010 projection from INSIC is also presented, as well as a realistic range for the 1 Tb/in^2 density point that sponsor companies are working towards. For the 4 Tb/in^2 point, both "Achievable" and "Stretch" values are offered, corresponding to roughly 60–100% and <60% chance of success, respectively. It is clear from the table that achieving the ~4.4 nm goal is a high risk, and it will require evolutionary as well as revolutionary changes in materials, processes, and clearance control schemes. HDD architecture (e.g., sealing in inert atmosphere) might also be needed [35]. This is discussed in the following sections.

4.1. Materials: Disk and Head Overcoat. It is clear from Table 2 that the biggest contributor to today's HMS is the carbon overcoat, both on the disk and on the head. Combined, they amount to about half of today's (aka 1 Tb/in^2) HMS budget. Historically, overcoat thickness reduction on both components has been enabled by denser carbon, as well as smoother underlying surfaces for the magnetic medium (disk) and RW elements (head). Head carbon has evolved from sputtered to plasma-enhanced chemical vapor deposition (PE-CVD) to filtered cathodic arc (f-CAC) carbon [36–39], which increased the density, sp^3/sp^2 ratio, and hardness [40]. On the disk side, f-CAC technology has not yet been made manufacturable [41, 42], mostly because of particle and deposition rate challenges, and most if not all disks shipped today are coated with some sort of PE-CVD deposited amorphous carbon overcoat. It is believed that disk deposition tools will soon need to offer new carbon technologies, able to closely emulate a high sp^3 bonded, f-CAC-type carbon film. On the head side, evolutionary optimization of the overcoat technology might allow to reach the 4 Tb/in^2 goal of ~1 nm, believed to be the ultimate coverage limit of f-CAC. Finally, although many attempts have been made by disk manufacturers to develop and ship noncarbon overcoated disks, it remains an open question whether any thin film materials other than carbon can be made as hard, dense, and chemically inert as carbon films [43–47]. The latter issue could be alleviated if HDD's can be sealed in an inert environment [35]. It is also believed that such a drastic change in the drive mechanical platform could help reduce overcoat thickness on both heads and disks, as magnetic medium and read/write alloy corrosion could then be suppressed, or at least drastically reduced. Our estimate of such benefit is in the range of 0.2–0.3 nm or greater, for an overall reduction of ~0.5 nm, that is, a substantial amount of about 10% of the total HMS. Another potential alternative is to develop a disk surface modification process such that the highly corrosion-susceptible media material surface is

Table 2: HMS breakdown scenarios for 4 Tb/in^2.

HMS Budget	1 Tb/in^2			4 Tb/in^2			HMS adder	
Components	INSIC 2010	Target HMS by ~2014		INSIC 2010	Target HMS by ~2020-21		(effect of HAMR, BPM)	
Component		Hi	Lo		Medium risk	High risk	BPM	HAMR
TDH	1.8	2.0	1.0	1.4	1.1	0.6	0.3	0.5
Disc overcoat	0.9	2.5	2.0	0.6	1.8	1.5	0.3	0.6
Disk lubricant	0.9	1.2	1.0	0.8	1.0	0.8		
Clearance	1.3	1.2	1.0	0.6	0.6	0.5	0.2	0.3
Head overcoat	1.0	2.0	1.5	0.7	1.1	0.9		
Total	5.8	8.9	6.5	4.0	5.6	4.3	0.8	1.4

The HMS adder columns corresponding to HAMR and BPM will be discussed in Section 4.

treated or modified without contributing to spacing loss with a creation of a nonfunctional or weakened layer of magnetic material on the media surface [48, 49].

4.2. Materials: Disk Lubricant. Table 2 shows that a 0.2 nm reduction of lubricant thickness from 1.0–1.2 to 0.8–1.0 is needed. This does not seem like much, but with today's extremely tight reliability/HMS margins, this change is actually significant, and it is believed that inventions will be needed to reach those goals [50, 51]. The lubricant industry is now more diversified than before, and new lubricant structures are now routinely offered by at least three different companies. It remains to be seen whether conventional lubricant chemistries (functionalized perfluoropolyether) will be able to achieve this thickness goal. Perhaps unconventional approaches, such as direct surface treatment/functionalization of the disk overcoat will be needed [48].

4.3. TDH: Topography. Touchdown height (TDH) globally defines all residual disk and head topographies that prevent the head from coming into close proximity to the magnetic medium (Figure 6). It is affected by waviness (~1–1000 μm wavelength range) and roughness (<1 μm) of the substrate [52–54], as well as the nanoroughness of the magnetic film-overcoat structure of the disk [55]. Unlike materials thicknesses (lubricant, overcoat), TDH is not a requirement for proper HDD reliability and could, in theory, be brought to zero. It assumed that engineering evolutionary optimization of polishing (disk substrate, slider) and deposition (media/overcoat) processes will be possible to achieve the HMS goal. Finally, it has been proposed that disk lubricant "roughness", both at the nanoscale (conformation) [56] and the microscale (thickness modulation or "moguls" [57] and "ripples" [58, 59]), also contributes to TDH, and lubricant optimization, as discussed previously, will be needed to also lower its contribution.

4.4. Head-Disk Clearance. Of all the HMS contributors, clearance has probably exhibited the largest decrease in the last 10 years or so, thanks to the advent of thermal flying height control (TFC-Figure 7) [19, 21]. This revolutionary approach has allowed the HDD industry to achieve a 10-fold reduction in clearance from ca. 10 nm ten years ago to ~1.5 nm today (Table 2). To achieve the 0.6 nm ASTC clearance goal and to easily compensate for clearance changes induced by temperature, altitude, or humidity, further enhancement of clearance control will be needed such as closed-loop TFC control. "Surfing" of light contact recording has also been suggested [26], but it remains to be seen whether this approach can be made reliable.

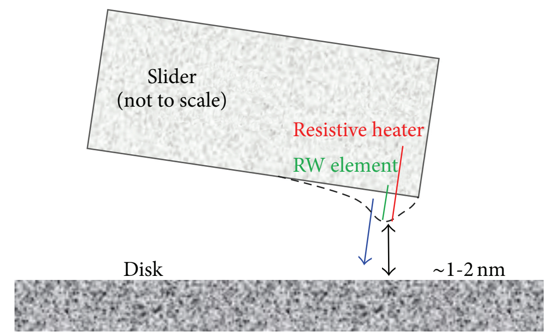

Figure 7: Schematics of the active fly height control scheme using an embedded resistive heater.

5. Tribology and HDI Challenges for Alternate Technologies

As discussed earlier, to advance HDD magnetic recording beyond the ~1 Tb/in^2 believed achievable with PMR/SMR, HAMR and BPM technologies are being developed. It is believed that HAMR will first be introduced. To go beyond ~6 Tb/in^2, the ASTC roadmap shows that HAMR will be augmented with BPM recording technology [11]. While these will enable significant gains in areal density, they will present challenges for the HDI.

In terms of HMS, the effect of these technologies is shown in the "HMS Adder" columns of Table 2. The touchdown height is increased due to added media roughness for HAMR or residual topography for BPM [32, 60]. The increased roughness also drives the need for added media overcoat thickness to maintain adequate coverage. With regards to clearance, HAMR would require added margin as a guardband for possible thermal protrusion of the near-field transducer (NFT) [10], whereas BPM will require clearance margin as a guardband against residual topography that could induce head wear. It is believed that BPM will not require head overcoat thickness adder.

As the HDD industry moves towards the introduction of HAMR recording technologies, there is a high demand for the HDI to demonstrate robustness at higher temperatures [30, 61–63]. If the current disk overcoat and lubricant films are not capable of withstanding the high recording temperature (>500°C), new materials will be needed. On the head side, it is currently believed that the temperature should be limited to ~ 150°C in order to provide long-term interface reliability to the current overcoat material. In any event, further development in tribological materials for both heads and media seem likely needed in order to insure proper reliability of the HAMR interface.

The later introduction of BPM recording technology will present further challenges for HDI design. Residual topography left behind by the BPM manufacturing process challenges air bearing designers to design a slider that can better follow residual topography [34, 64, 65] as well as media manufacturers to have a uniform overcoat and lubricant coverage of the media surface. Moreover, the residual media topography could lead to excessive induced lubricant roughness on the microscale (lubricant moguls and ripples) unless a new lubricant can be designed.

6. Conclusion

In summary, head-media spacing continues to be an enabler for continued march to increase the areal density to fend off the assault and encroachment by nonvolatile solid-state memory technologies. To maintain HDD leadership and competitive edge in the data storage arena, the industry must continue to develop new component technologies to support this areal density advance. However, to be successful, the design of the head-disk interface must be an integrated effort where the component technologies are developed in concert to solve the system problem. The success of the areal density growth will depend on how successful we, as an industry, are in integrating this development.

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