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MICROSCOPE EQUIPMENT FOR
NUCLEAR EMULSION ANALYSIS

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James C. Hodges

Lawrence Radiation Laboratory
University of California
Berkeley, California

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Berkeley, California

February 1960

ABSTRACT

A comprehensive survey of microscope optics and mechanical equipment most suitable for observing and measuring nuclear tracks in photographic emulsions is given. The problems of adapting commercial instruments and of building special microscopes to handle large emulsion sizes are discussed. Considerable attention is given to the design and fabrication of mechanical stages. Included are extended-travel scanning and measuring stages for attaching to conventional microscope stands, as well as more massive stage types for building into custom equipment. Special aids toward increased efficiency in handling large volumes of emulsion are discussed, with emphasis on the selection and installation of digitizing equipment.

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INTRODUCTION

Instruments currently in use for emulsion-plate study vary widely in structural design and in the number and complexity of mechanical components. Basic equipment is often a conventional laboratory microscope fitted with a small precision measuring stage weighing perhaps five pounds. For accurate measurements of high-energy particle tracks, instruments with mechanical stages weighing several hundred pounds are in general use. The now widely used 6X9-inch and larger emulsion sizes require modified or custom-built units to accomplish even the basic scanning routines. The emulsion volume of current large stack exposures becomes astronomical when each linear dimension is multiplied by 500 or more diameters of magnification. This situation calls for a new class of emulsion microscopes stressing highest operational efficiency throughout, including automation for many routine procedures.

Whatever the mechanical or structural variations, one component is common to all successful emulsion microscopes to date--a visible-spectrum optical system. Conventional compound microscope optics and transmitted illumination are normally employed. Essentially the same optical specifications are applicable to all binocular-vision emulsion instruments. Thus, optical equipment will first be discussed in some detail, with stress on application to specific analysis procedures, rather than to particular microscope types. Structural design and mechanical features of emulsion microscopes will then be described, using a somewhat arbitrary sequence of instrument types to accommodate both the reader whose main interest is commercially available equipment, and the custom designer.

* Variations have concentrated mainly on the use of special objectives--such as reflecting or monochromatic types. Some success with incident illumination on opaque-backed, thin (50-micron processed) emulsions is reported.

I. SUITABLE MICROSCOPE OPTICS

Optical components for the emulsion microscopes will in most cases be carefully selected from those used on, or designed to fit, standard laboratory microscopes. Eyepieces and objective lenses (including those especially made for nuclear emulsions) are readily interchangeable on all standard microscope mounts. The substage condenser and the microscope illuminator should be selected as carefully as eyepiece-objective combinations, both for building into custom instruments and for use on commercial microscope stands. These items are not as readily interchangeable. Adaptors, or some modification of a conventional stand, may be required. The inclined binocular body is the least interchangeable optical component. Yet the superiority of a particular prism arrangement, the need for a specific inclination angle, or a preference between converging and parallel eyetubes, must often be considered.

Some preferred binocular body style should not dictate purchase of a microscope otherwise inferior for emulsion work. Where conflict exists, certain stands (as later noted; see p. 36 and also Fig. 9, p. 45) can be readily adapted to take a variety of binocular-body styles.

Thus, by selecting judiciously, emulsion groups may acquire optical components of superior quality and combine at will those best suited for each particular emulsion type or analysis procedure. Once the microscopist has set up and brought these components into precise optical alignment, he can rest assured that though his microscope stand be the simplest laboratory model, the image he observes through the eyetubes of his preferred binocular body will be as clear and accurate an approximation of the emulsion recorded event as that achieved by a highly engineered scattering microscope.

A. Above-Stage Optical Components

An objective lens for primary magnification and an eye lens, or ocular, compounding this magnification make up the compound microscope system. The specified distance, or tubelength, between these components is accomplished on most emulsion microscopes by a third component, the inclined binocular body, whose optical properties must also be considered. With standard illumination, the theoretical maximum of resolvable magnification for this system was achieved many years ago. Indeed, some experts assert that modern lens design and quality is retrogressing rather than advancing from the plateau of excellence attained in the 1920's. Recent innovations, however, greatly facilitate emulsion microscopy and it may be possible by testing and comparing to find individual lenses equalling, if not surpassing, earlier types in performance.

1. Objectives

The objective is, of course, the compound system's most critical component. The greatest angle at which its front lens element can accept diffracted light from the specimen determines the maximum resolving power and therefore the normal magnification limits of the microscope. This

angular collecting ability is marked on all objective housings in terms of numerical aperture (NA). * From two to fourteen additional lens elements accomplish the objective's listed magnification: varying amounts of chromatic and spherical aberration correction; and in certain special objectives considerable increase in working distance, flatness of field, etc. Whatever its internal variations, this lens system must maintain a close-tolerance back focal length consistent with standard 160- or 170-mm tubelengths.

Magnification values marked on the objective are close approximations, but the specified NA, working distance, tubelength, and the general image quality to be expected from the particular achromat, fluorite, or apocromat element assembly should be verified before accepting a lens for use. Rejects returned to the manufacturer from various research groups can help towards a stricter adherence to advertised performance, saving the microscopist the effort sometimes spent in sorting out one good item from a shipment of objectives bearing identical markings. One may have to pay from \$50 to \$100 more for an objective of listed NA 1.40 than for a similar objective of NA 1.32. It is then disconcerting to find that the aperture of the more expensive lens measures only 1.35 or 1.36 -- a considerable price to pay for a scarcely detectable increase in resolution.

Many objectives giving outstanding performance in general biological or medical work have only restricted application to emulsion microscopy. In fact, few conventional high-aperture objectives can be used with the thicker emulsions of current high-energy programs. Selection of objectives for various analysis procedures as well as different emulsion thicknesses will depend on some of the following considerations:

a. Achromat, fluorite, or apochromat: Fortunately, this choice is less critical in the grey-scale photographic emulsion medium than in work with polychromatic specimen. For general emulsion work, the lower-powered achromats are corrected adequately and are preferred over apochromatic types owing to modest cost, greater stability of the comparatively simple lens structure against mishaps with awkward-sized emulsion strips, and often, longer free working distances. The limited spherical - and chromatic-aberration corrections of the achromat are less adequate at high objective powers.

* $NA = n \sin \theta$, where n is the refractive index of the medium between object and objective lens, and θ is the extreme angle with respect to the optic axis at which light from the object can be accepted. Since the front element is normally a sphere with a flattened lower surface, θ is actually the half angle subtended by the lens at the object. Thus the greater the NA, the shorter the working distance.

Since n for air is unity, a "dry" lens must subtend an impossible 180-deg arc of light to achieve an NA of 1.00. With immersion objectives and oil of about the same index as the emulsion gelatin (1.51), numerical apertures in the vicinity of 1.40 are attainable, with a theoretical maximum at 1.5.

In powers of over 70x, or apertures much over 1.00, semiapochromatic fluorite objectives may provide truer image fidelity.*

Well computed fluorites will equal the performance of the more fully color corrected apochromat objectives for most emulsion work. Moreover, longer free working distances and less field curvature are frequently obtained. Apochromats have some slight advantages for critical measuring work and photomicrography, especially where strong blue filters are used. They pair better with compensating eye pieces for extreme total magnifications. In most cases, individual apochromats can be expected to vary less from listed performance specifications than individual high-power achromats or fluorites.

b. Dry and oil-immersion objectives: Oil-immersion objectives are of course mandatory for resolutions requiring an NA of over 0.95. They are also best used where objective powers of over 25x or NA's between 0.50 and 0.95 are indicated. Dry objectives in this range normally are computed with corrections for cover glass. Even when available with variable correction collars, they require tedious and frequent adjustments to maintain image quality as sloping particle tracks are followed through changing thicknesses of emulsion. However, where an all-dry objective complement is essential, "high-dry" types which perform well with emulsions up to 150 microns processed thickness can be obtained.† Numerous metallurgical microscope objectives are computed for use without cover glass; Leitz and Koristka each make a dry objective specifically for emulsion work. (A series of suitable high dries is included in Table I, p. 18.)

c. Free working distance: The spacing achieved between the lower extremity of an objective and the object at its focal point determines the objective's usefulness with the thicker emulsions. This spacing varies inversely with the numerical aperture, and to some extent with the power, of the objective.

* Although there is some variation among designers, the achromat normally corrects for two wave lengths of color and for spherical aberration in only one wave length. The fluorite objective combines a single fluorite element with glass lens elements to bring off-wave lengths much closer to common focus. Secondary spectra are greatly reduced and spherical corrections in two wave lengths are attained. The apochromat utilizes several fluorite elements to reach three chromatic and two spherical corrections.

† Dry objectives of NA greater than 0.40 are not recommended for thick emulsions. A deterioration of image quality is unavoidable as corrections for an air medium compete with varying thicknesses of emulsion.

Working distances reach listed minimums of about 50 microns for conventional 92x to 98x apochromats of NA 1.40. To this may be added the 160 microns normally allowed for cover glass,[†] for a total of 210 microns -- scarcely adequate for a processed strip of 400-micron emulsion. No presently available NA-1.40 objectives provide the working distance of 320 or more microns essential for full penetration of processed 600-micron emulsions. Choice is restricted to a few standard achromats and fluorites in the 1.20 to 1.30 NA ranges. Emulsions in the 800-micron range (400 to 450 microns thick after processing) exclude most objectives of over 0.65 NA. No standard objectives are adequate for 1000-micron emulsions, although these have become increasingly important in both high-energy accelerator and cosmic ray research.

Fortunately, some 12 special objectives are available for most current emulsion thicknesses. The Cooke, Troughton, and Simms Company makes three, all with NA's under 1.00 but with over 1000 microns of free working distance. The more comprehensive Koristka series deserves to be better known. Included are several unique low-power high-aperture objectives (more fully discussed on p.17) as well as the only commercially available high-power objective of over 1.00 NA and 500 microns working distance--a fluorite, 100x/1.25 NA achieving 530 microns working distance.

The special "Ks" series of Leitz, designed specifically for nuclear emulsions, is widely used in 600-micron work. The series includes three immersion objectives, the highest a 100X apochromat of NA 1.32 and working distance of 370 microns.

d. Depth of focus is inversely proportional to both magnification and NA. This fact, although unfortunate for general microscopy, is often beneficial in critical nuclear-track analysis. Accurate Z-coordinate measurements, normally made with the microscope's fine-focus unit, require an absolute minimum depth of focus in order that "Z" values fall within the accuracy range of

[†] Working distances specified in catalog data on standard immersion objectives are often confusing. They are usually given as free distance above a particular cover-glass thickness prescribed for general laboratory microscopy (160 microns for high apochromats, 170 or 180 microns otherwise.) However, one should be suspicious of any exceptionally long working distances listed, as the cover glass dimension may already have been incorporated. Aside from ascertaining this factor, one should assume that working distances may be as much as 20 microns under the specified figure.

Working distances listed for, and usually inscribed on, special long working distance objectives normally indicate total free space between objective and object. This again is not always consistent: the 100x Leitz Plano apochromat, NA 1.32, is often rejected for emulsion work, not merely for its high cost, but because the listed working distance of 270 microns is inadequate. Actually, the 14 lens-elements of this flat field objective achieve a working distance of 270 microns plus a cover glass allowance of 160 microns, for a total of over 400 microns!

the other spatial coordinate measurements. One should choose a measuring objective with due consideration that standard biological objectives are designed for as great a depth of focus as possible.

e. Flatness of field: A slightly spherical field of view is a necessary sacrifice to other corrections in standard lens designs. For procedures demanding accurate off-axis Z measurements, and particularly in photomicrography, special aplanatic objectives having a superior degree of field flatness are useful. Their high price, limited working distance, and inability to parfocalize with standard objectives prohibit more general applications.

Special objectives of all types should be carefully inspected for performance. Extended working distance, flatness of field, etc., can only be gained at the expense of some other, perhaps equally important, lens property.

2. Nosepieces

Although a purely mechanical device, the nosepiece is extremely important to the optical system. It must assure precise centering and alignment of the objective's optical axis with that of both the substage optics and the binocular body. Most nosepiece types and makes are easily interchanged with a makeshift wrench. Thus the microscopist should select and install a well-designed nosepiece most closely suiting his analysis procedures.

a. The bayonet design is still preferred on certain measuring instruments. Each objective must be fitted with a special collar provided with centering screws. This in turn twist-locks into a fixed nosepiece receptacle. Once the centering screws on its collar are set to the desired accuracy, an objective may be removed and reinserted with confidence that its alignment is precise.

b. The revolving nosepiece permits considerable speed-up in general scanning and analysis procedures. On some models as many as six objectives are held ready for fingertip selection. When parfocal objectives are used, less than half a turn of fine focus readjustment is required as each objective is swung into place for specimen observation under a sequence of magnifications.*

Durable as well as precise revolving nosepieces are essential where event-identifying and "following-through" procedures require extensive interplay of objectives, and where there is the possibility of bumps and jars while handling awkward-sized emulsion plates. Types most suitable will provide

* If due care is exercised, a particular group of objectives may be fitted with machined shim washers at their shoulders to increase mutual parfocality. Shims lowering the objective more than 1/16 in. are not advised. Misplacement of the objective's back focus as well as optic axis misalignment must be considered. The new series of Zeiss (West Zone) objectives as well as the excellent Leitz Plano series are physically too long for parfocal assembly with standard objectives on a revolving nosepiece.

a positive periphery contact of the rotating member with the full circumference of the mounting disc, rather than depend on a small central hub for both rotational and aligning support. The detent stop should give positive centering action without undue frictional wear; this is best achieved through use of a spring-loaded bearing ball.

The weight factor of special emulsion objectives should be considered when several are mounted on a multi-orifice nosepiece. A triple or quadruple design seems adequate for most emulsion procedures. There will be less wear on both the nosepiece and the fine focus mechanism.

3. Binocular Bodies

While the tubelength of monocular microscopes may be adjusted to suit any objective's back focus, the binocular body presupposes a standard, predetermined tubelength. This distance, measured optically from the objective's shoulder to eyetube extremity, becomes critical with higher aperture objectives. Tubelength problems may often be traced to auxiliary lenses inserted at the base of many binocular-body housings. When these are incorrectly computed or of poor quality, they cut down appreciably on resolving power and image brilliance.

In designing special equipment or in adapting a microscope stand to take a binocular body of a different make, the additive or subtractive tubelength compensation of auxiliary lenses must be taken into account.

Many modern binocular bodies contain a built-in magnification factor of which the user may not be aware. Prism arrangements supplying unit magnification permit larger field size and greater illumination with the same amount of light than those with a built-in magnification factor.

In emulsion microscopy binocular bodies with parallel eyetube extensions have certain advantages. The microscopist need not readjust interpupillary distance when switching between short standard oculars and the higher positioned wide field pairs. The mounting of adequate goniometers is more easily accomplished with parallel eyetubes. Whatever the binocular body style, it is imperative that prisms be optically excellent and mounted in holding frames of sufficient rigidity to prevent misalignment from jarring due to frequent interchange of eyepieces and the manipulation of goniometer, filar micrometer, and other measuring accessories.

4. Oculars

The two-element Huygenian negative ocular and the simple Ramsden positive ocular are infrequently used in emulsion microscopy. However, modifications of one or the other of these basic types are incorporated in more suitable eyepieces, and at least where a micrometer disc, or reticle, is to be used, it is important to determine whether the ocular is of positive or negative type. The negative ocular derives its designation from a lower or field-lens element inserted below the point where the primary image from the objective would normally be formed. This lens has a negative effect on the image, slightly reducing it before its final magnification by the upper, or eye lens unit. In the positive-type ocular, all lens elements are normally

above the point where the primary objective image is formed.

The simple Hugenian and other negative type eyepieces are often unsuitable for use with measuring reticles. Lens imperfections will affect the image and the reticle in unequal amounts. A focusing device for the upper lens unit is usually necessary to provide adequate scale and image-plane coincidence for fine-ruled reticles such as described on p. 25. Positive type oculars offer little problem in reticle fitting; many are provided with either fixed or adjustable micrometer disc platforms. This platform will be coincident, or nearly so, with the field stop or diaphragm of the eyepiece.

A diaphragm is nearly always incorporated in an ocular sleeve; it offers the easiest method of determining the basic type. If all lens elements are above the diaphragm, the ocular is positive; when the diaphragm is between lens units, the ocular is usually a negative type.*

Intermediate correction oculars assure more adequate retention of image quality from objectives of NA 0.50 or above than can be achieved by the simple two-lens types. Used with high power objectives, they provide maximum flatness of field. Hyperplane, Periplan, Kellner, Orthoscopic are major trade names of eyepieces of this class. All are widely used in emulsion microscopy, although the Hyperplane and Periplan have a negative lens structure.†

Compensating eyepieces form a still more highly corrected series. They employ carefully computed over-corrections to compensate for certain difficult-to-correct defects of apochromatic objectives. Compensating oculars are not recommended for general emulsion work. Their fine lateral color compensations are not essential for this grey scale medium; moreover, they introduce serious over-corrections of the primary image from most achromatic and fluorite objectives. Even with high-aperture apochromats, compensating oculars give a decidedly greater field curvature than the

* Certain Ramsden oculars are provided with a plain glass disc below the diaphragm to serve as a dust shield. A troublesome feature of basic Ramsden oculars is that any foreign matter adhering to the exterior surface of the lower element is seen in sharp focus.

† Leitz and Koristka 10x and higher periplanatic oculars have a below-diaphragm corrective element of very weak negative effect. Even when a focusing upper-lens unit is not incorporated, a careful trial-and-error repositioning of the diaphragm platform will usually achieve an optimum position where reticle focus and image plane coincide.

intermediate correction types.* Negative lens structure is a further disadvantage of low power compensating oculars. The positive compensating types of 20x, 25x or higher power do, however, have an important application where reticle measurements are required at maximum total magnifications; orthoscopic positive types are rarely available in these high ocular powers.

Wide-field eyepieces provide an enlarged field of view highly advantageous for many scanning and measuring procedures. Positive-type wide fields are extensively used. In most cases, excellent reticle focusing properties more than compensate for the poor color correction and lack of field flatness inherent in this type. The 10x Tiyoda and Zeiss models give an intermediate increase in field while sacrificing less in image flatness. Spencer and B&L 10x models provide maximum possible increase in field diameter--nearly 1-1/2 times that of a standard 10x--but introduce considerable curvature. Negative-type wide-fields assure a flatter image than any of the above, and are preferred for work not requiring measuring reticles. Leitz offers 10x, 16x, 20x, and 25x wide-fields in its well corrected periplanatic series.

Further increase in field area would be of great value in several phases of emulsion microscopy. e. g. to allow rapid scanning at higher magnifications, and to minimize both the labor and the uncertainty involved in examining areas around complex particle-collision and decay events. At present, maximum field area is physically limited by the approximately 0.917-inch inside diameter of all binocular body eyetubes (and, of course, corresponding prism surface areas). Many monocular instruments are now using a larger diameter tube and comparable ocular to achieve field areas far beyond the maximum for conventional wide-field eyepieces. Rumors are that at least one major manufacturer will soon have available a binocular body microscope of similar capacities.†

* These shortcomings of the Compensating eyepiece are noted by Shillaber in his excellent text on photomicrography.²

They are, moreover, amply illustrated through a series of comparative photographs taken by Professor J. E. Gullberg, Zoology Department, University of California, to determine the relative retention of primary image quality by various types and makes of oculars.³

† The first evidence of this is a new Metalograph by Leitz (Model MM), having a binocular body with approximately 1-1/4-inch I. D. eyetubes, and oculars of comparable diameter. Designers may find the possibility of incorporating these components in a conventional microscope system worth investigating.

Special eyepieces: Oculars incorporating measuring devices will be discussed under "Optical Measuring Accessories," Section I-C. Amplifying eyepieces for photomicrography, screen projection, and other applications not directly related to binocular vision systems, are reserved for a future UCRL report on Specialized Optics. (See footnote p. 129)

Quality of oculars, since they are machine-produced, varies little with individual units but markedly between various makes and types. Inadequate eyepieces reinsert many of the optical defects so painstakingly eliminated by highly corrected objectives. It behooves the microscopist to carefully select a paired set of eyepieces giving high-fidelity image rendition in the range of objectives to be used, and, for measuring work, a sharply delineated reticle focus that is coincident with the image plane.

5. Ocular-Objective Combinations

Total magnification for a microscope with unit power binocular body is approximately the product of objective and ocular powers. In emulsion microscopy, combinations must be chosen to cover all or most of the following magnification ranges:

- a. 100x for preliminary alignment checks--of light sources, etc.
- b. 200x to 300x for rapid preliminary scanning, taking grid-coordinate readings, etc.
- c. 500x to 800x range for much general scanning, also for work normally carried out at higher magnifications, but lowered due to lack of illumination in fogged emulsions, or to pellicle thicknesses beyond working distances of high objectives.
- d. 900x to 1200x for critical scanning, such as the following of "minima" tracks, for high-energy range and scattering measurements, for much grain-density work, especially in overly thick or dense emulsions.
- e. 1500x to 3000x for grain-and gap-counting procedures with heavily ionized tracks, and for discrete vertical measurements requiring a minimum depth of focus, e. g. determining the relative spatial position of two track grains in contact. *

The pairing of optimum-performance oculars and objectives to encompass this wide range of magnifications is a project of considerable difficulty.

* At a given NA, the higher the total magnification, the shallower the depth of field. Leitz recommends its 100x 1.32 Ks objective to be used at 3000x total magnification to obtain focusing accuracies of ± 0.2 micron.

Suitable specific units will of course vary with performance limitations of a particular microscope's substage optics, with emulsion types and thicknesses to be used, measuring-eyepiece requirements, and the minimum resolution essential for the particular analysis procedure. However, some general selection guides might be listed:

a. For greatest efficiency where several magnifications are frequently alternated, a revolving nosepiece is best fitted with either all-dry or all-immersion objectives, chosen to achieve values most used when combined with a single set of oculars. A complement of parfocal immersion lenses is recommended for processed emulsion thicknesses of over 150 microns.

b. The objective's numerical aperture determines both the limits of resolution and the permissible range of magnification for any ocular-objective combination. A factor of 250 times the NA of the objective is sufficient magnification for all resolvable detail to be seen*. For example, an objective of NA 1.40 (the highest NA available for emulsion work) need only to be paired with an eyepiece giving a total magnification of 350x for the normal eye to barely distinguish as separable entities two ionized grains with centers approximately 1/4 micron apart. With white light this is the maximum resolution obtainable for any NA-1.40 objective and ocular combination. Additional magnification will not further separate the two grains nor add any more detail to the field of view.

However, one may increase this "empty" magnification to a factor of perhaps 1200 times the NA of the objective--or to about 1700 diameters for the above example--without greatly endangering the image quality, providing the microscope has excellent optical components throughout. The high-power NA-1.25 to -1.32 long-working-distance objectives most used in 600-micron emulsion work reach upper limits for crisp resolution between 1400x and 1500x.

c. Working within but near the upper limits of resolvable magnification has advantages for much general emulsion work. It aids the microscopist having eyes of lower resolving ability than that of the theoretically normal eye. It gives larger general outlines which are easier to "see," especially in connection with many estimating and comparing procedures. Indeed, as noted above, certain work is carried out at 2000x to 2500x -- far above the upper limits of resolvable magnification, even though detail is lost amid general image fuzziness.

d. Conventional microscope optics are universally computed for optimum performance near the upper limit of resolvable magnification. The general rule given by major manufacturers is that the eyepiece should be chosen to assure total magnifications of 1000 times the NA of the objective.⁴

* This value is determined by the human eye's ability to resolve detail. In the compound microscope it is equal to the NA of the objective divided by the NA of the microscopist's eye. The numerical aperture of the normal eye of 2-mm diameter is calculated at 0.004 mm, or 1/250 mm. Thus the normal magnifying power equals objective NA times 250.

Expert microscopists recommend broadening the range to include values between 500 and 1000 times the objective's NA.⁵

e. Recent studies have shown that (at least with thick, fine-grain emulsions) less image distortion and better over-all definition can be achieved by changing the very one-sided ratio of high-powered objectives and low-powered oculars normally used to achieve best working magnifications with conventional optics.* For instance, the customary Leitz 100x NA-1.32 Ks objective must be used with a 10x ocular to obtain 1000x magnification. A 50x objective and a 20x ocular give the same total magnification with a much better ratio of component optical powers. Primary image distortions reaching the eyepiece measuring reticle or filar micrometer will be greatly reduced. A 50x NA-1.35 objective is the highest power objective supplied with the new, ultraprecise, Zeiss-Jena scattering microscope. Koristka has provided a series of compatible low-power high-NA objectives for its special emulsion microscopes.

These and rare conventional objectives of the same type offer the following possible advantages in general emulsion analysis:

a. High resolution at low total magnifications: a 30x/1.10-NA objective can be used with 10x wide-field oculars to give nearly double the resolving power normally available at 300x. Even with 10x or higher oculars, near maximum resolutions are possible in the much used 500x to 800x range with 50x/1.35, 65x/1.25 and similar special objectives now available.

b. Low-power high-aperture objectives permit the use of a large selection of high-power oculars without overstepping maximum resolvable magnification limits. These include the excellent 15x, 16x, 20x, 25x, 30x 'periplantic' standard and wide-field types of major European microscope manufacturers.

c. Longer working distances are more easily incorporated in these objectives. The types listed above can all be used with emulsions of 600 microns' actual processed thickness.

Table I contains a list of objective-ocular combinations which have been found useful in various scanning and analysis procedures, mainly at this Laboratory, and at other research centers closely connected with the U. S. Atomic Energy Commission. The list is intended only as a very general guide; certainly many other makes and types of objectives as well as oculars are currently in use for the same emulsion tasks and may perhaps be more efficiently applied. (Emulsion thicknesses are given in preprocessed state.)

* Nuclear emulsion groups at both Brussels and Milan have reported that the "best" images were obtained with a Wild-Fluotar 50x NA-1.00 objective and 20x GF Leitz ocular combination.⁶

Table I

Objective-ocular combinations	
Objectives	Oculars
<u>Dry Objectives</u>	
1. B&L, Leitz, 10x/0.25-NA	1 and 2 with 5x hyperplane, 6x periplan, 10x wide-fields for alignment and preliminary survey procedures with all emulsion thicknesses.
2. B&L 21x/0.50	
3. Koristka 26x/0.65	3 to 6 with 10x to 25x positive or Periplan types for scanning and analysis with emulsions to 300 microns maximum.
4. Cooke (M1422) 40x/0.85	
5. Leitz Ks 47/0.65	
6. Reichert (Flusme) Fl. 95x/0.75	
<u>Oil immersion, Emulsions to 500 microns</u>	
1. Leitz 22x/0.65/500 microns	1 with 5x, 6x, 10x intermed. correction oculars.
2. B&L Fl. 40x/1.00/400	2, 3, and 4 with 10x W.F. B&L for max. field scanning, with same or 10x, 15x Kellner for max. reticle coplanarity; with Leitz GF 16x, 25x for grain counting, etc.
3. Leitz Fl. 70x/1.30/350	
4. B&L Fl. 98x/1.30/300	
5. B&L Apo. 61x/1.40/280	
6. Cooke Apo. 80x/1.32/280	5, 6, and 7 with above, but also B&L 15x, 25x and Zeiss K20, K30 compensating types.
7. Leitz Apo. 90x/1.32/280	
<u>Oil immersion, 600-micron emulsions</u>	
1. Leitz 22x/0.65/500 microns	Oculars used are in general the same as listed for group B. The Leitz 10x GF gives a flatter image with Leitz and Koristka special objectives than the B&L W.F., but the field area is not as large, and reticle focus is less dependable.
2. Leitz Ks Fl. 53x/0.95/1000	
3. Cooke Fl. 45x/0.95/400	
4. Leitz KS Apo. 100x/1.32/370	
5. Koristka 55x/1.00/700	
6. Koristka Apo. 65x/1.20/600	
7. Koristka Fl. 100x/1.25/530	
7. Koristka 30x/1.10/1000	With 4, 6, and 7 B&L 25x and Zeiss K20, K30 compensating types used for minima track and grain and gap analysis.

Special combinations

1. Leitz PLANO Apo. 100x/1.32/420 2. Koristka 30x/1.00/3000 microns	With Leitz GF 10x for max. image flatness, and with Leitz GF 25x for distinguishing minute increments of vertical separation. With Zeiss K20 and K30 for track following through emulsion "sandwiches." This combination is successfully used at L. R. L. (Livermore) for following-through procedures involving two 600-micron pellicles each mounted on standard 1.5-mm glass plates. See A. E. Dyson, A Follow-Through Plate Holder for Nuclear Track Microscopes, UCRL-5544, April 9, 1959; see also Fig. 1.

Maximum-working-distance objectives, emulsions to 2000 microns and over

1. Cooke 25x/0.65/2000 microns
2. Cooke 45x/0.85/1500
3. Leitz Ks/22x/0.65/2200
4. Koristka 30x/1.00/3000 microns
5. Koristka 55x/0.90/1350
6. B&L Fl. 40x/1.00/1500 (special order)

New objectives now in limited production

1. Leitz L591 100x/1.32/700 microns
 2. Zeiss HI 50x/1.00/1900
 3. Zeiss Monochromatic HI 50x/1.35/600
-

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Fig. 1. A follow-through plate holder developed by the Dr. Stephen White emulsion group, L.R.L., Livermore. Used with a Koristka 30x objective of 3000 microns' working distance, it permits the mutual alignment of consecutive plates (two 6 by 12-in. plates are shown) so that tracks may be directly followed from one 600-micron pellicle to another. The microscope is a Bausch & Lomb "Dynotic;" the basic stage is a L.R.L. large-plate scanning stage.

B. Substage or Illuminating optics

In bright-field microscopy, maximum image quality is normally dependent on two specimen illuminating requirements: a highly corrected substage condenser of numerical aperture equal to or greater than the objective's NA, and a well-collimated light source providing either true Koehler or true critical-type illumination. Experience indicates that the thicker photographic emulsions used in nuclear research do not require strict adherence to either of these classic precepts.

1. Substage condensers

Most emulsion analysis is done with "dry" condensers, even where high NA objectives are essential. This procedure is partly dictated by the extreme inconvenience of maintaining an oil bond between condenser top and large emulsion plates, but more specifically from direct observation that in most cases immersing the condenser achieves no measurable image improvement. It is not fully understood why a 1.30 NA objective resolves as efficiently with a dry condenser whose illumination cone will theoretically never exceed NA 1.00. The light-diffracting and-scattering properties of the ionized and background silver grains doubtless effect some increase in angular aperture of the light cone reaching the objective. It is also evident that the working distance of standard high-aperture condensers is too short for their full NA to be utilized effectively with the 1/16-in. -thick glass mounts of many current emulsion plates. When a high-aperture condenser becomes available with a working distance matching that of the special objectives described above, it is quite possible that condenser immersion will show a more definite improvement in particle-track resolution.

Until such time, the well corrected NA-1.40 achromatic condensers are best reserved for critical measuring work and photomicrography. A high-performance, though less color-corrected aplanat -- usually of NA 1.30 -- is offered by certain German and Japanese concerns. Both of these types may be used with oil if desired. For scanning and much general analysis the simple two-lens Abbe condenser--somewhat facetiously marked NA 1.25 -- will prove most useful. Its greater working distance and light-gathering capacity permit adequate use of low-power finder objectives. Where considerable large-plate scanning work is contemplated, the simple Abbe has decided economical assets. Scratched, chipped, or even dislodged upper condenser elements may be frequent; cost of repairing or replacing an Abbe-type condenser is about one-fifth that of the achromatic.

A condenser component essential for emulsion work is an externally located iris diaphragm. Since the iris is used both as an aperture control and a means for optically aligning the substage with above stage optics, the adjusting mechanism must operate smoothly and be capable of closing the iris leaves to produce a small, well-centered orifice. Certain Berek-type condensers, provided with an additional between-lens iris, have insufficient light-gathering properties for 600-micron emulsion microscopy.

Many condensers, especially of the corrected type, are mounted in a spring-loaded centering device. When constructed so that there is an extreme minimum of permissible tilt about the optic axis, these centering devices are

helpful alignment aids for photomicrography (and perhaps for more general use where the operator is an expert microscopist.) For routine work on larger emulsion sizes, they should be avoided, or at least modified so that once adjusted, the movable components may be clamped solidly in that optimum position.

Variable-focus condensers operating on the principle of mechanical separation of condenser-lens elements, and most helical-focusing mounts are inadequate for emulsion work. Standard rack-and-pinion focusing mounts will be discussed in the section on conventional microscope stands.

2. Light Sources

Some twenty years ago Zeiss designed a "pancratic" condenser, incorporating light source and substage condenser in one integral unit. Renewed interest in this optical approach is evidenced by a number of similar designs recently placed on the market. Theoretically, this is the most efficient arrangement of substage optics possible. It permits use of a very-low-wattage lamp with correspondingly small filament area, most nearly achieving ideal point-source illumination. The troublesome field lens of standard light sources is replaced by a variable-focus first element of the condenser. Thus full control is obtained over both the field area illuminated and the angle of the light cone (the condenser's NA) to match the exact requirements of both very-low-and very-high-power objectives. This arrangement may offer the best approach toward the long working distance condenser urgently needed for 600- and 800-micron emulsion work. Unfortunately, current designs seem more concerned with the compactness of the system than with the optical quality achieved by the now-discontinued Zeiss prototype. One problem may limit wide application of even the best engineered of these devices to general emulsion microscopy -- the inaccessibility of controls. They are hidden immediately beneath oversized mechanical stages and large emulsion-plate accessories.

Simple light sources designed to fit directly beneath standard condenser mounts, and those incorporated in the microscope base, suffer from the same inconvenience of adjusting controls, as well as providing, in the main, insufficient light intensities for thicker emulsion work.

At present, the best approach to efficient emulsion illumination is offered by high-intensity light sources, separate from, but mounted firmly on a common base with the microscope stand. Here again an axiom for peak resolution in compound microscope optics is seemingly disregarded with impunity. Usually, neither true-critical nor Koehler illumination is used. Critical illumination, requiring the radiating source itself to be imaged in the object plane, is of course not adaptable to the conventional tungsten filament. True Koehler illumination requires a near approximation to a point source and a high quality collecting or field lens which becomes a second radiator source. The filament is projected on the substage iris and the field lens projects its white-hot circle of light (if the lens is good) in the object plane.

In emulsion microscopy, modifying the Koehler principle with a finely ground diffusing filter in the immediate vicinity of the field lens achieves a more brilliant and evenly illuminated field of view. Grain resolution in the

thicker emulsions seems actually to improve. Scattering or interference effects peculiar to photographic emulsions may partially account for this, but one suspects the diffusion filter's major role is counteracting the combined defects of large-area filaments and notoriously poor field lenses in most current light sources. The geometry of the Koehler system, however, should be retained for best results. This calls for a microscope illuminator adequately designed and properly positioned to image its lamp filament (with diffusing filter temporarily removed) on the condenser iris, and its field lens in the emulsion plane. A prerequisite for this type of illuminator is an adjustable field stop located immediately in front of the lens assembly. It is usually sufficient that the closed-down iris leaves of this stop, rather than the less discernible field-lens surface, be sharply imaged in the emulsion plane.

Illuminators incorporating ribbon-filament, or even vapor-arc lamps and the best available aspheric field lenses (optically ground rather than cast) may be indicated for photomicrography and certain critical measurements. For more general work, and especially where greatest operational efficiency from large-plate scanning microscopes is to be attained, the following design features should take precedence:

- a. Full control of light intensities, with peak output adequate for thick, high-density emulsions.
- b. Conveniently located controls for maintaining precise optical alignment from the lamp filament itself through to the substage condenser. Many scanning procedures call for exacting light-path alignment. The slightest deviations are both easily detectable and highly disconcerting to an experienced scanner spending hour after hour racking his objective up and down through 300 or more microns of vertical travel. With awkwardly placed or crudely functioning facilities, much productive time is lost to realignment tasks accompanying a scanning objective change, a lamp replacement, an accidental bump of condenser or substage mirror.

Experience has shown the conventional substage mirror to be the worst offender. Large scanning stages make its location highly inconvenient. Extensive apprenticeship is required to master the pushing and twisting of its double swivels to achieve the optimum reflecting plane. With no protection from dust and immersion-oil drippings, the more optically efficient first-surface type is soon scratched and dulled from cleaning.

Microscopes with built-in illuminators have well housed mirrors, but often no external adjustment facilities are provided. At least one external light source has solved the mirror problem in similar fashion. It is designed with an extended neck to project under the substage condenser. As an integral component of the light source, a first-surface mirror is housed in this extension. Rapid three-dimensional adjustments of the mirror are effected through external thumbscrews.*

* This is the Ortho Illuminator made by American Optical Co. (see Fig. 9, p. 45). It is a high-intensity unit, well adapted to large-plate scanning requirements. The design, however, limits its use to open-foot microscope stands, and where the tilting facilities of inclination-joint-microscope types are used, the approximate angle of tilt should be duplicated for the illuminator's exit lens. Adapters for this purpose can be furnished by the manufacturer.

c. The diffusing filter mentioned above, as well as color, heat, and density filters (to be discussed next), should all be placed near the illuminator's field lens for best results. An efficient scanning illuminator should provide facilities for rapid selection and insertion of various filter combinations into the optical path.

3. Filters

Several filters in addition to the diffusing screen have important application to emulsion microscopy.

a. Neutral filters replace, or at least supplement, the over-worked variac and rheostat. Electrical control of lamp intensity should be kept close to the lamp's rated wattage if color temperature is not to drop excessively. A series of neutral filters allowing specified percentages of light transmission will give stepped intensities covering the full gamut of magnification and emulsion-strip opacity variables. For intermediate values, fine adjustments of the illuminator iris or the electrical input can be made without exceeding maximum performance limits. Bausch and Lomb manufactures an excellent series of four neutral filters, in values from 50% to 6-1/2% transmission. Certain illuminators offer rapid-change devices for comparison selection of neutral filters, or similar types combining a diffusing surface and stepped opacities.

b. Heat-absorbing filters: Normally, the presence of a diffusing filter eliminates danger of melting or burning for most emulsion types when 6-volt 5-amp, or 110-volt 100-watt lamps of the coil-filament type are used. Yet instances of emulsion melting are noted at even these wattages when the path between filament and emulsion consists solely of short air gaps and high-efficiency condensing lenses. Under these circumstances, and when a high-amperage 6-volt or a 200- to 300-watt projection lamp is employed, a filter of special heat-absorption glass is essential for minimum protection. Carbon- and vapor-arc sources and even low-voltage high-amperage ribbon-filament lamps usually require 1-1/2 to 2-in. -thick water cells to absorb the heat rays effectively.

c. Color filters: Several are extensively used in emulsion work. The slight bluish tint of the so-called "daylight" filter helps counteract the predominant red values of tungsten light which are irritating and produce eye-strain during lengthy scanning sessions. The solid-glass daylight filters supplied with most standard illuminators are not adequate for this purpose. A thickness of about 6 mm is required for effective red-value damping with normal light intensities used in emulsion work; since this thickness is awkward for most filter holders, the daylight filter is not extensively used for scanning work.

A green filter is far more efficient in damping the red values of tungsten light. In addition, it gives maximum transmission to the wave lengths best adapted to optics used in general emulsion work. The human eye is most sensitive to "apple" green. Optical components such as the Abbe or aplanatic condensers and achromatic or fluorite objectives have their best (or only) spherical color corrections computed for the green wave lengths. Even the fully

corrected apochromats can be expected to perform better when accepting green light from the uncorrected Abbe or aplanatic condenser.

Practical application of the green filter shows two definite field-of-view improvements: a marked reduction of glare from background grains, and an improved crispness of the object image itself. Many scanning technicians use a light- or even medium-green filter almost exclusively, although an occasional switch to the daylight filter is often restful during long sessions at the microscope.

A strong blue filter provides maximum use of the shorter visible-spectrum wave lengths, and thus increased resolution. A suitable blue filter, preferably used with a mercury-arc source, will permit up to one-third greater resolution for an apochromat-objective and achromatic-condenser combination. Grain-separation problems in dense tracks, measurements of track width, scattering measurements, and photomicrography are applications for the blue filter. It should be noted that a strong blue is tiring to the eye, and irritation from the longer ultraviolet wave lengths is possible during extended sessions at the microscope.

d. Interference filters: Color filters can insure a maximum of light transmission in their spectral color only and a proportional absorbing effect on complementary colors. However, interference filters will select very narrow wave bands or, with monochromatic light, a specific spectral line for transmission. Their application to emulsion microscopy is at present extremely limited by two factors: while comparatively high-intensity illumination is already a prerequisite for the thick emulsions, still higher intensities must be provided to offset the low transmission properties of interference filters. These filters are most effective when used with special monochromatic objectives corrected for the same wave lengths. The selection of monochromatic visible-spectrum objectives is as yet much too limited for general emulsion procedures.

Filters, in general, should be of good optical-quality glass, either of the solid-glass type (such as the Corning) or the gelatine type sandwiched between two layers of optical glass (such as the Wrattan series). Solid-glass green filters of good quality are difficult to obtain from many illuminator or microscope manufacturers. Best results may require standard or custom-cut sizes ordered directly from a manufacturer of optical filters. Since color saturation in solid filters depends on their thickness, it is well to specify the intensity and type of light source to be used. Table II lists some suggested filters.

Table II

Suggested filters		
	<u>Solid glass</u>	<u>Gelatin sandwich</u>
Neutral density	B&L #31-34-67 20% Transmission B&L #31-34-68 10% Transmission	
Heat absorbing	Corning aklo 1-59	
Medium green	Corning 4-68	Wratten 54, 58
Deep green	Corning 4-74	Wratten 62
Medium blue	Corning 5-59, 5-60	Wratten 2A
Deep blue	Corning 1-64	Wratten 47

In recent years, microscope substage optics have ranged far from the conventional devices described above. Some of the important developments are dark-field, monochromatic, and ultraviolet illumination; light-wave manipulation through polarization, phase contrast, and interference techniques. Emulsion microscopy has yet to investigate these fields thoroughly.

C. Accessories for Measuring in the Optical Path

1. Eyepiece Micrometer Discs, or "Reticles"

With the exception of low-powered Huygenian eyepieces, one of each ocular pair used on the emulsion microscope is normally fitted with an engraved glass disc, or reticle. Simple crosshair reticles are used for optically aligning the instrument and as reference coordinates where all measuring is being done by mechanical stage or goniometer. Grid and concentric-circle rulings are used for subdividing the field of view itself. Finely ruled scales, carefully calibrated to a specific objective's magnification, achieve precision field-of-view measurements. Variations and combinations of these basic designs make the reticle an extremely versatile tool. Two general factors determine its maximum utility in any given task. It must be accurately positioned so that its rulings appear sharp and opaque in the precise plane of the object image.*

* Measuring errors are often tracked to parallax between reticle scale and image. Coplanarity can readily be checked by holding one's eye at least an inch above the ocular and making quick head movements. Both scale and object points should move together if parallax has been eliminated.

For optimum results, each reticle should be custom-positioned for the dominant eye of the individual microscopist.

Secondly, the reticle must facilitate the particular analysis problem without cluttering or distorting the field of view. This indicates good optical-quality glass and scrupulously clean surfaces. The configuration should be no more elaborate than necessary for the task at hand, and lines should be held to a minimum width for clear perception at the particular magnification of the ocular.

Standard photoetched reticles are inadequate for most emulsion work. Fine rulings must be made directly in the reticle glass with a diamond or other appropriate scribing tool. Major optical companies will supply individually ruled reticles to specification. However, both cost and delivery time are considerable for intricate patterns or close-tolerance scale rulings. Establishing specifications for a particular reticle to be custom ruled is a task of no mean proportions. Some variables to be considered are:

a. For a reticle to give desired intervals of measurement in the field of view (micron integers are most convenient), its scale should theoretically have unit spacings equal to the product of the desired field of view interval and the power of the objective to be used. Yet, to achieve any near approximation to the desired field of view interval, one must consider an individual objective's tubelength correction, the particular binocular body's optical tubelength, and (for negative oculars) the magnification factor of a lens element below the reticle position.

b. Total area of a ruled configuration which can be accommodated in the field of view is directly determined by the ocular's diaphragm stop. The diameter of this opening varies inversely with the ocular's power, although wide-field oculars have correspondingly larger openings. The diaphragm of most 10x wide-field types is nearly coincident with the inside diameter of the ocular tube.

c. The fineness or width of suitable line rulings will vary with ocular magnification. Rulings just discernible in a 5x ocular will be five times broader than necessary if the reticle is used in a 25x ocular. Density extremes of emulsions in use must be considered when attempting to hold line widths to a near minimum.

* Leitz and Koristka objectives are normally corrected for a 170-mm tubelength. When used with a standard 160-mm tubelength binocular body, a Leitz 100x will require an eyepiece reticle with scale divisions 130 microns apart to approximate 1-micron intervals in the field of view. A 100x objective of many other makes, when used with a Leitz binocular body, requires less than 100-micron scale divisions to achieve the same 1-micron field-of-view intervals. Furthermore, individual objectives may show an astonishing variation from the 160- or 170-mm tubelengths they are supposedly designed to meet.

d. A good fit in the ocular barrel, or a provided reticle seat, is essential where angular or aligning measurements require well-centered rulings. Reticles which fit one eyepiece may be several millimeters too large or too small in diameter for eyepieces of other makes or powers.

When working out specifications it is helpful to lay out the proposed reticle on a blank disc as carefully as possible with a diamond hand scribe, and then study it in the optical system for a check on field-of-view dimensions, scale-unit spacings, etc. Actual line widths to be specified are best determined by securing sample rulings from the reticle manufacturer.

2. Method of Custom-Ruling and Fitting Reticles at L. R. L.

Research groups with diversified emulsion programs may find it advantageous to manufacture their own reticles. A small ruling engine built for this purpose at the Lawrence Radiation Laboratory is shown in Fig. 2. An experienced operator using a manually operated device such as this can rule the 100-division reticle scale with superimposed cross hairs and "boxing-in" lines shown in Fig. 3 in about twenty minutes.* The L. R. L. machine has turned out several thousand reticles. Many of these are duplicates, quickly run off from operating schedules giving dial readings for each translation of the basic two-coordinate stage -- one coordinate providing precision interval spacing, the other translation of the reticle glass beneath the lowered diamond stylus for the actual ruling of each line.

The procedure for reticles of new design is relatively simple. The microscopist submits a rough sketch of the pattern as he wishes it to appear in the field of view, along with a notation of the optics to be used. If the ocular takes a nonstandard reticle diameter, it is sent along for fitting. In this case, the separate cut-out stylus is swung into place and the graduated turntable revolved for cutting glass trial discs. The setting of the cut-out stylus which produces a disc precisely fitting the ocular is noted and later used in cutting out the finished reticle. The actual ruling is done on a sheet of optical-quality No. 3-thickness coverglass clipped to the turntable surface. From a tentative schedule several sample reticles of the sketched pattern are run off with variations in spacing and widths of line rulings (fineness of line may easily be varied through weighting the diamond stylus). The samples are returned to the microscopist for comparison in his instrument. Since actual spacings and line lengths on the reticle are known, he has only to measure their projection on the field of view with his measuring stage or a stage micrometer to arrive at accurate ratios for any dimensional changes. As is often the case, he may find his original pattern included several conflicting or superfluous lines. Dimensional and pattern changes, and line width desired can easily be accommodated by the scribing-machine operator in making the final custom-fitted reticle.

* Few commercial concerns will undertake a design of this type where a cross-hair line bisects the scale graduations. It presents little problem on a hand-operated machine when proper weighting is applied to a carefully chosen diamond.

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Fig. 2. A reticle-ruling engine, developed and operated by the Accelerator Technicians' microscope service group at L.R.L., Berkeley. The cut-out stylus has been swung into place over the turntable. The ruling diamond is visible beyond with its counter-balanced mounting frame and precision pivot axis. The dial at the left is used for spacing advances between rulings. The other dial knob moves the stage and the reticle glass beneath the lowered ruling stylus. A portion of a "schedule" is seen in the background.

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**Fig. 3. Measuring reticle for 25x eyepiece. Scale rulings:
100 divisions at 40-micron spacing. Width of individual rulings
is approximately 4 microns.**

3. Goniometers - Precision Goniometers Made at L.R.L.

Although reticles are sometimes ruled with radiating lines of given angular separation, field clutter becomes excessive with intervals of much under 15 deg. Accurate angular measurements to 1 deg, or even 0.1 deg can be made with a crosshair-provided eyepiece clamped to an appropriate goniometer. The goniometer is usually constructed of two close-fitting parts: a body with provisions for clamping to the binocular eyetube corresponding to the operator's dominant eye, and a rotatable barrel into which the ocular is inserted and clamped. One of these units will have a calibrated dial plate, the other a reference fiducial, or fiducial and vernier scale. Maximum dial diameter, to the point of conflicting with the other eyetube, can be obtained with the dial plate forming part of the rotating unit or barrel.

Commercial goniometers are available with high-precision dial graduations, but few incorporate the following features essential for efficient emulsion microscopy:

- a. A barrel of sufficient length to provide adequate clearance for the nose of a sharp featured microscopist, and a dial diameter of at least 2-1/2 in. so that 1-deg division marks may be spread out sufficiently for easy perception.
- b. Provisions for taking wide-field oculars, and certain standard designs without extending the microscope's tubelength, thus eliminating need for recalibrated reticle scales and a spacer ring under the companion ocular.
- c. Precision fitting of parts so that the ocular is both held in line with the optical axis, and maintains this alignment as it is rotated. A well designed goniometer will effectively eliminate the normal looseness of ocular fit in the binocular eyetube. It can thus contribute to greater accuracy of linear as well as angular measurements.

The outside diameter of binocular-body eyetubes varies as much as 0.050 in. among microscope makes, and the variation among ocular types (at the points where the goniometer barrel can be clamped without disturbing tubelength) is even greater. The precision of the best goniometer will be lost owing to the shimming or boring out required to adapt it to an eyetube or ocular other than that for which it was made. Thus, where diversified equipment is in use, the only adequate solution is a series of custom-built units, each machined to close-tolerance fits for a specific optical combination. A goniometer in general use at L.R.L. is shown in Fig. 4. The basic barrel and body are each machined in a number of bore sizes for several binocular-body and ocular types. The dial plate and vernier sets are purchased from commercial engravers and mounted for easy replacement when worn or dulled. The dial plate can be turned separately to provide convenient zero settings for the reticle without disturbing the ocular in its clamp. Close-mating tolerances are held so that several barrel components, each fitted with a different ocular and reticle combination, may be interchanged at will on the same permanently installed body component.

Body

Barrel

Assembly

ZN-2431

Fig. 4. Goniometer with zero-adjusting and replaceable dial ring and vernier.

4. The Filar Micrometer

This is an important optical accessory for precision measurements in the field of view. It consists of a special eyepiece to which is fitted a micrometer-screw mechanism which advances a hairline over a fixed reticle scale (or in some designs a scale is moved over fixed reference rulings.) Fine-pitched micrometer threads are used. Once the unit is accurately calibrated to a particular objective, measurements of extremely small increment may be read directly from the graduated drum actuating the leadscrew. The filar micrometer is extensively used in scattering measurements but is poorly adapted for general use on the binocular-body microscope, since a companion ocular is difficult to pair with it.*

5. Optical-Path-Deviation Micrometers: Poohstrilino, etc.

The minute micrometer increments necessary for track-width and multiple-scattering measurements have occasional revival of the optical micrometer devised over a century ago by Clausen. Rotational turning of parallel glass plates is used to shift the objective's primary image in the eyepiece. This optical-lever advantage permits field-of-view intervals as small as 0.01 micron to be accurately determined on such models as Koristka's Poohstrilino tube (Fig. 5).

Both the new Leitz-Stodiak scattering-stage optics and the Zeiss-Jena scattering microscope utilize similar Clausen-type micrometers. At present, no models directly adaptable to standard binocular-body eyetubes are available. Also, the device is restricted by image displacement available in current optics to a total measuring range of about 20 microns.

* Some filar micrometers employ Ramsden-type optics, others Huygenian. All have special diaphragm orifices or lens formulas to compensate for the additional tubelength required to house the filar mechanism.

The only adequate solution for a companion ocular seems to be inserting in the other eyetube an identical filar-micrometer unit with the engraved scale removed and replaced by a clear-glass disc of equal thickness. This is not practicable in some Ramsden filar units where the scale is actually engraved on the plane surface of a plano-convex lens element.

ZN-2435

Fig. 5. Poohstrilino tube, equipped for use on the Koristka MS-2 scattering microscope.

II. ADAPTABLE CONVENTIONAL MICROSCOPE STANDS

Custom-built microscopes and the several commercial instruments designed for nuclear emulsion work are usually reserved for critical measuring procedures or other specialized techniques. Basic scanning and much general particle analysis are efficiently carried out on standard laboratory microscope stands, equipped with selected optics and special mechanical stages.

The choice of a proper stand is complicated by recent design trends. Many well known laboratory models have been discontinued in favor of compact, minimum-weight instruments featuring built-in illumination and stage-actuating focus controls. Few of these are capable of meeting the requirements of both operator convenience and mechanical endurance for full-time large-plate scanning procedures.

A. Basic-Stand Requirements for Emulsion Work

Basic stand requirements for emulsion work are:

a. A base of sturdy construction and preferably of the open-foot rather than the pedestal type to accommodate external illuminator units more adequately.

b. The arm rising from the base to support the above-stage optics must also be exceptionally sturdy and vibration-free. A design less common in current models provides an inclination joint between arm and base. This has certain advantages. Tilting the microscope arm about this fulcrum permits selecting the most suitable binocular-body inclination for widely varying scanner physiques. It also solves an otherwise difficult problem of light-source clearance when large mechanical stages are used.

c. Substage construction must include a strong, nonflexing support arm for the condenser unit; broad, well-mating dovetail surfaces; and smoothly operating rack-and-pinion mechanism with a conveniently located control knob for precise vertical adjustment of the condenser along the optical axis.

d. The stage-support bracket must be adequately constructed to provide a broad upper surface for bolting on a separate mechanical stage and supporting it in a plane precisely perpendicular to the optical axis. Models where the stage bracket forms an integral part of a built-in mechanical state are unsuitable.

e. Coarse- and fine-focus mechanisms: In almost continuous operation during emulsion work, these focusing devices must have precision-fitted, wear-resistant components.* All working parts should be removable for repair or replacement by a competent maintenance technician. Where a mechanical stage weighing more than two or three pounds is to be used, it is essential that the fine-focus mechanism be designed to actuate the above-stage optics, rather than the stage platform.

f. Low-positioned fine-focus heads: Although this adds to the complexity of the actuating mechanism, the fine-focus knobs or heads should preferably be located not more than 3 in. above the base of the stand. Usually two heads are provided, one at either end of an actuating shaft running through the arm. They should be free-turning, of adequate size for easy manipulation, and one head must incorporate a drum dial graduated directly in micron increments of Z travel. Moreover, the actual Z-coordinate (vertical-focus) travel must remain consistently linear for any repeated arc of head movement throughout the rotational limits of the mechanism. Calculations--and possible digitization of this movement--are greatly facilitated if the drum dial makes exactly one revolution per hundred microns of linear focus travel.

g. Microscope stands which are intended for use with large-dimensioned emulsion plates--9x12 in. or even 6x9 in. if fitted with a substantial holding frame--should permit modification for increased throat capacity without major surgery.

B. Recommended Stands

Perhaps none of the fifty or more current laboratory-microscope models has a stand fully meeting all the above requirements. Among the nearest may be mentioned the Bausch and Lomb "Dynoptic" series, the Leitz "UB" stand, certain Tiyoda "L" research stands, and the Zeiss-Jena "Lg" stand.

The Leitz "UB" is perhaps the only conventional microscope stand with a throat clearance adequate for scanning to the center of 9-in.-wide emulsion strips. Unfortunately, it retains high-positioned fine-focus heads.

* The coarse focus may be racked up and down a full inch or more every few minutes to facilitate exchange of large emulsion plate sequences in "following-through" procedures. Area scanning and similar procedures in thick emulsions require almost continuous manipulation of the fine-focus knob back and forth through 300 microns or more (at least three full revolutions) of travel. This adds up to between 500 and 1000 times the daily wear and tear if the microscope were used on the standard biological and medical slides for which it was designed. Microscopes "built to give a lifetime of trouble-free service" will often develop serious fine-focus noise within a year of emulsion scanning use.

The B&L "Dynoptic" stands feature an excellent low-positioned fine-focus unit; the standard 4-in. throat may be increased without much difficulty to a full 5-in. or more (see Fig. 7, p. 43). A 15-deg tilt of the arm about the inclination joint is necessary to bring the body tubes--inclined at only 30 deg from vertical--down to a more convenient 45 deg angle. However, both the "Dynoptic" and the "UB" stands may be fitted with adapters to take various binocular bodies, including Spencer and other converging types (Fig. 9, p. 45).

The above-mentioned Zeiss and Tiyoda models have no inclination joint. Pedestal-type bases are customary, but open-foot bases will be supplied on request. Their low-positioned gear-train fine-focus mechanisms operate well, but are somewhat delicate for thick-emulsion scanning procedures. Worn gear trains, however, may be removed as a unit and new ones quickly installed. Since other Tiyoda models and laboratory microscopes made by the two West German Zeiss companies are stage-focusing types, one must be careful to select the exact model desired.*

Two other microscopes offer low-positioned fine-focus heads for actuating above-stage optics: The Reichert "Z" stand, and the Koristka "Euskop." Neither of these units has a stage-support bracket integral with the basic stand. This, though a detracting feature for normal application, could prove advantageous where special mechanical stages having a cross section too thick for standard mounting are to be used.

C. The Reversed Stand

At first appraisal the Leitz "Ortholux," Cooke "Universal," Reichert "Zetapan," and similar multipurpose laboratory microscopes seem ideally suited for emulsion work. The positioning of the arm away from the operator, rather than between him and the stage area permits a more massive and mechanically rigid construction of the entire stand. It also provides unobstructed access for easy manipulation of awkward-sized emulsion plates and for changing objectives or applying immersion oil to them. Mechanical stages on these models are superior to most laboratory types.† Numerous special features include conversions for photomicrography; dark-field, phase-contrast, incident illumination; etc.

* Here also might be mentioned the Cooke M25 and M35 series, of design very similar to the Zeiss stage-focusing models. The M35 series provides an interesting variation: the coarse focus still actuates the stage, while the fine focus, placed low and coaxial with the coarse-focus heads, actuates the above-stage optics. Conceivably, the M35 model could handle a mechanical stage weighing 8 to 10 pounds.

† Special emulsion stages available for the Ortholux and the Cooke Universal are discussed in Section IV-B, p. 51.

Unfortunately, the widely advertised universality of these instruments does not extend far into the nuclear emulsion field. Indeed, for much high-energy work the reversed-stand advantages will be outweighed by the following features that are difficult to modify:

a. Stage-actuating focus controls, prohibiting the use of heavy special stages,* or of stage-coordinate digitizing encoders.†

b. Built-in illuminating systems, although greatly improved on recent models, still present problems in adequate alignment and intensity control. Substitution of a preferred external illuminator is usually not feasible.

c. The basic reversed design creates a difficulty that is often overlooked. Any emulsion strip wider than the instrument's throat depth (usually 4 to 5-1/2 in.) must project its full width toward the chest of the observer when peripheral areas are being studied. Six-inch plates become awkward for feminine scanners; nine-inch plates require feats of contortion.

Most of the advantages and fewer disadvantages of the above reversed-arm microscopes may be achieved on certain conventional stands. The Tiyoda and Zeiss models mentioned earlier in this section have rotatable binocular bodies. It is only necessary to turn these 180 deg to make a reversed stand. Also, the Leitz "Ortholux" binocular body can be directly attached to the UB stand to achieve a reversed microscope with full 5-in. throat.

III. STAND-ATTACHABLE TRANSPORT AND MEASURING STAGES

Special mechanical stages are required for most emulsion work. A stage which can be directly attached to a conventional microscope stand without conflict between its rotating or coordinate travel members and the optical or mechanical components of the microscope requires considerable ingenuity of design. At best, some sacrifice of maximum structural and dynamic stability must be made. Measuring accuracies approaching those of elaborate scattering microscopes cannot be hoped for. However, stand-attachable stages can provide such valuable features as the following:

*The Cooke M4000 series, although using a stage-actuated coarse focus applies linkages from low-positioned fine-focus heads to actuate the nose-piece section only of the above-stage optics. This feature has valuable applications which will be discussed more fully in the section on Commercial Emulsion Microscopes, Section IV-B.

† Currently available shaft encoders will add too much weight to even a light two-coordinate stage when directly coupled to its lead-screws. The up-and-down focusing movement of the stage poses extremely complex coupling problems for encoders (or even motor drives) when these are mounted apart from the stage.

- a. Two-coordinate travels of as much as 5X5 in.
- b. Slow, easily controlled advances, measurable in 1-micron least intervals.
- c. Short travels giving accuracies to within 2 microns composite lead error and stage noise per 1000 microns of linear travel.
- d. Facilities for supporting and translating emulsion sizes to 9X12 in. or even larger.
- e. Systems for plate reiteration and for its rotation about the optical (or other) axes.
- f. Motor-drive units for automatic coordinate advance, or even full digitization of stage coordinates with all mechanical equipment installed directly on the microscope-supported stage.

These features, of course, are not all obtainable on any single stage; nor is it good design practice to attempt a sort of universal, or "all-purpose" unit for attaching to a standard microscope stand. For best results the stage unit should be chosen, or custom-designed if necessary, to meet the specific analysis procedures and even the specific emulsion-strip sizes of a projected research program.

Procedures used by various emulsion groups in outfitting conventional stands with serviceable mechanical stages will now be discussed.

A. Standard Laboratory-Microscope Stages

Although no current models are suitable for general emulsion work, standard microscope stages are often the sole recourse of small emulsion groups without facilities for designing and building special equipment. They are also perhaps the only solution for groups who must utilize stage-focusing microscope equipment already at hand.

Certain of these stages, when carefully modified and fitted with auxiliary measuring devices, are quite serviceably employed for basic analysis work on the smaller emulsion sizes. Most suitable is a superior two-coordinate design offered by Leitz, Cooke, Tiyoda, and others. The Y coordinate movement (toward and away from the observer) which is so unsatisfactory on most conventional laboratory stages, * travels on ball bearings

* In conventional two-coordinate stage design the Y movement is achieved by a stage plate mounted on two sets of ways straddling the substage condenser. The driving mechanism must be placed much nearer one set of ways than the other, or by means of double racks and pinions one must attempt to apply equal torque in the vicinity of each way slide. Whatever the method, extreme minimum of inertia or extreme rigidity of sliding and fixed members is essential to overcome a coupling effect, observable in the field of view as a wandering X displacement each time the Y movement is actuated. Coupling, even where two sets of racks are used, becomes more and more pronounced with stage wear, posing extensive maintenance problems.

in precision-fitted raceways, rather than the usual lightweight dovetail slides. These stages are sturdy enough to permit the following modifications:

- a. Slowing down of the rack-and-pinion or multithread lead-screw driving mechanisms which provide a transport too rapid for careful scanning and too coarse for accurate positioning of events to eyepiece fiducials. Considerable improvement can be realized by the simple expedient of increasing the diameters of the driving knobs or heads to a maximum within available space.
- b. Provisions for support of the emulsion plate during the X coordinate travel, rather than the customary method of merely shoving it along over the stage table by means of slide-clip fingers projecting from the X-coordinate actuating mechanism.
- c. Provisions for reiterating emulsion plates of larger than 2×3 in., which is maximum two-coordinate travel for most laboratory stages.
- d. Although critical measurements are not possible on stages of this type, it is often helpful to install auxiliary measuring devices to decrease the 100-micron least-interval readings provided. Special dial indicators may be obtained with up to 3-in. capacity and reading in 10-micron least units. The Leitz and Tiyoda ball-bearing stages may be purchased already outfitted with such indicators (see Fig. 6).

Additional refinements could be suggested, but the cost and machining involved is usually better spent on a fully custom-designed unit.

B. Adaptable Stages of Commercial Manufacture

An increasing number of measuring stages of fair to excellent performance are now commercially available as separable components or accessories for optical comparators, metalographs, toolmakers' microscopes, etc. Stages that have been designed for use with transmitted light are essentially built around a large central orifice of dimensions commensurate with coordinate travels, so that the substage condenser will not be overridden by a moving component. Such stages may often be adapted to a sturdy laboratory microscope stand. Units with thick cross sections may require lowering the stage support bracket; large over-all dimensions may require deepening the microscope throat. Actuating heads and measuring scales may need relocating. However, such modifications are a far simpler undertaking than building a complete stage.

In addition to problems of fitting, the cost of these special stages is often a deterrent factor. Units with travels of over 2 in. and fair measuring facilities may cost well over a thousand dollars, although comparable stages of Japanese manufacture are now available at considerably less than this figure. The following current makes may be worth investigating:

Fig. 6. Ortholux mechanical stage.

ZN-2436

- a. Two-coordinate measuring stages for the Nikon Optical comparator, Model III. Both coordinates on ball-bearing raceways, fine micrometer screw advance, travels of 2X6 inches (unfortunately, only achieved by reiterating and inserting gage-block spacers) on large models.
- b. Stage accessories for Tiyoda, Union, and other Japanese-made metalographs and toolmaker's microscopes. Limited travels but fine measuring increments and added rotational features.
- c. Stages for the new Bausch & Lomb contour projectors and toolmaker's microscopes--built by Doall Machine Tool Co.
- d. Two-coordinate stage for the Swiss-made Projectina optical comparator.
- e. Leitz may soon have in commercial production a large-emulsion-plate stage with 5X15 cm travels.

C. Custom-Built Stages for Conventional Microscope Stands

A third approach, confined mostly to research groups with extensive design and machine-shop facilities, is the custom stage, built for the specific microscope stands, emulsion sizes, and research procedures of the group concerned. This is not an easy solution. Storage closets of various laboratories contain numerous abortive prototypes.

1. European and American Designing

The use of ball-bearing raceways is quite consistent on European custom stages. Designs are similar to the above-mentioned ball-bearing laboratory stages, usually with full-sized translating superstage rather than slide clips for the X coordinate. Fine-pitch lead screws or special micrometer head units replace the rack-and-pinion drives. Concentration on small emulsion-strip sizes permits these designs to include special rotational and tilting features not feasible on stages requiring more extensive travels. An interesting example is the Slatis stage described in Section V-B.

Most custom designing in this country is distinguished by the use of heavy dovetail slides, or similar mating-surface slides, in place of ball-bearing raceways. When adequately constructed, a single dovetail unit suffices for each coordinate movement. Moreover, a large-diameter lead screw can be directly incorporated in such a unit to remedy the offset-drive instabilities of conventional laboratory-stage design, and to accomplish greatly extended coordinate travels. While developing higher frictional inertia, large area metal-to-metal contacts are free of the incipient chatter effects of ball-bearing raceways; maintenance problems due to normal wear, accidental jarring, or overloading of point contact balls, are effectively eliminated.

This method of construction is successfully employed in two stage types developed at the Lawrence Radiation Laboratory and now in use as standard equipment on emulsion microscopes both here and at various other research centers. A brief description of the latest models may be of interest.

2. A Compact Measuring Stage Developed at L. R. L.

Although this unit is more massive than standard laboratory stages, it may be termed "compact" when compared to many custom designs. Its lightest version weighs 6 pounds, which prohibits its use on stage-focusing microscopes, but is not excessive for direct attachment to microscope stands similar to those recommended in Section II-B. It is specially designed for diversified scanning and measuring procedures where maximum efficiency does not require a Y coordinate travel of over 2 in.

a. Construction features: The stage is essentially is baseplate and two self-contained "way units." A massive one-piece dovetail guide of hardened tool steel, a mating aluminum slide block, and a large-diameter 1-mm-pitch precision-ground lead screw comprise each way unit. These may be combined in any of several mutually perpendicular arrangements on a 6X6-in. baseplate designed for bolting directly to a Bausch and Lomb "Dynoptic," or similar microscope stand. Calibrated dials, verniers, and linear scales provide accurate full-travel readings in 1-micron least units. Maximum coordinate travels and corresponding tolerances for lead error or stage "noise" vary with the particular coordinate assembly chosen.

b. Assemblies: Two quite distinct stage types are possible utilizing the same basic components.

Model II (Fig. 7) is primarily a scanning stage with an unencumbered stage table or "superplate" for translating a wide variety of emulsion sizes through 2 in. of Y travel, and 4, 6, or even 8 in. of X travel, depending on the length of the X way unit chosen from stocked sizes at hand.

Model I (Fig. 8) is essentially a "slide-clip" measuring stage, although adequate supporting frames rather than conventional clips are normally used to carry the emulsion strips, thus eliminating all sliding contact with the stage table. Standard microscope throat depths limit Y coordinate travels on this model to 1-3/4 in. Travel in the X direction is again 4, 6, or 8 in.

Best dynamic stability is achieved in the Model I design. Measuring accuracies of ± 2 microns per 1000 microns travel can be achieved for both coordinates when a 4-in. X way unit is used in the assembly. Some increase in stage noise and lead error accompanies installation of the longer X units.

3. A Large-Plate Scanning Stage Developed at L. R. L.

This stage (Fig. 9) was primarily developed for efficient scanning of 6X9-in. and larger dimensioned emulsion plates. It is normally attached directly to a conventional microscope stand, with some additional bracing to support its 17 pounds' weight. Most of this weight is concentrated in the exceptionally heavy dovetail way units. These are assembled in a configuration similar to, but more structurally rigid than, the Model II compact stage. Superplates as large as 19X25 in. are often used so that emulsion plates to 9X12 in. may be freely reiterated without any overhang of sharp glass edges.

ZN-2434

Fig. 7. The L.R.L. compact measuring stage, Model II. Travels on this particular unit are 5x11 cm. Both the upper and lower spacer blocks used to increase throat capacity of this B&L Dynoptic stand are visible.

ZN-2432

Fig. 8. An extended version of the Model I L.R.L. compact measuring stage. This unit handles $2\frac{1}{2} \times 15$ -in. emulsion plates with only a single reiteration required. The X travel is 20 cm. A Y travel of $2\frac{1}{2}$ in. is obtained with the aid of spacer blocks to extend the throat capacity of the B & L "Dynoptic" stand.

ZN-2438

Fig. 9. This microscope is fitted with a L. R. L. large-plate scanning stage. Travels on the stage shown are 12X12 cm. The microscope unit is a hybrid -- a B & L "Dynoptic" stand fitted with throat-increasing spacer blocks, and a Spencer binocular body with converging eyetubes. The light source is an American Optical Co. "Ortho-illuminator."

This stage has evolved through several years of design effort to become both a scanning and a two-coordinate measuring instrument of fair precision. Some fifty units are now efficiently employed for all analysis procedures except that of multiple scattering. Specifications for the latest model include:

a. Uninterrupted travel in either coordinate of 120 mm (approx. 4-3/4 in.) which permits area scanning of 144 cm² of emulsion without time lost in plate reiteration.

b. Smooth, well-controlled advances, measurable in 1-micron least units throughout full travels. Readout facilities include conventional drum-dial and linear-scale combinations, geared rotation counters reading direct to micron digits, or provisions for direct attachment of analog-to-digital converters.

c. Final accuracy limits compounded of lead error, readout error, and total stage noise are difficult to compute for extended-travel stages. Accuracies within 1% are easily achieved on this model; accuracies within 1/2% (or a maximum error of five microns per 1000 microns) can be held throughout full coordinate travel only when the stage unit combines extreme precision-machining of parts with expert hand-lapped assembly.

Many custom stages achieve better measuring accuracies than the models just described. However, few of these with comparable travels can be mounted on conventional microscope stands. A detailed analysis of design problems and structural limitations of mechanical stages in general is undertaken in Section V, p. 71.

IV. COMMERCIAL EMULSION MICROSCOPES

Some half-dozen microscopes specifically outfitted for nuclear track analysis are in limited commercial production. The number has tended to decrease rather than increase with expanding emulsion programs of the last few years. Few models have kept pace with research in the higher-energy fields. Here, expanding emulsion sizes demand greater stage-platform areas and a corresponding increase in microscope throat depth. More extensive travels along each stage coordinate become necessary for efficient scanning and range measuring. Regardless of emulsion size, measuring accuracies for high-energy multiple scattering and related procedures must now hold to a few millionths of an inch. The most successful commercial microscopes have been those designed primarily for the evaluation of high-energy scattering.

A. Scattering Microscopes

Measurements of Coulomb scattering in nuclear emulsions yield some of the most important data for high-energy particle identification. The Coulomb effect of adjacent emulsion atoms induces curved irregularities in the trajectories of all charged particles. At lower energy levels the

resulting track undulations can often be adequately measured with conventional microscopes-stand and precision-stage combinations described above.

At 100-Mev levels and beyond, the increasingly minute amplitudes of these local deflections can only be effectively evaluated on special scattering microscopes. Current models are capable of measurements to energies of 10^{10} electron volts, where Coulomb deflections are on the order of 0.1 micron or less. The mechanical limitations of the scattering microscope may well be a major deterrent to the study of still higher-energy particles soon to be produced artificially, and already being captured in emulsions retrieved from the fringes of outer space.

One may appreciate the precision required of an instrument where consecutive Y distances of as little as 0.1 micron each must be measured from a base line of X coordinate travel representing the mean straight trajectory of an undeflected particle. * To obtain even 10% accuracy, the X stage movement must have less than a 0.01-micron Y deviation from absolute linearity between successive measuring intervals. Scattering microscopes are thus essentially designed around an X-axis stage as free as possible from deflections or "noise" in the Y direction.

The Y noise level, usually designated as $\bar{D}$, for a specified distance or cell length of scattering stage movement is the major criterion in evaluating a particular instrument. † However, other features contribute to the scattering microscope's over-all performance and to its adaptability for a particular emulsion program:

* The most used "sagitta" method involves taking Y ordinates of the track's curved irregularities at fixed intervals (cell lengths) of X travel--often as many as 200 measurements per centimeter of track. The mean scattering angle is calculated from these purely linear measurements. Computations include taking second, or even third, differences of the Y values, and are so extensive as to normally require mechanical or electronic computer facilities.

Other methods utilize direct angular as well as linear measurements of increments of the scattering curve. Computations are simpler, but extremely precise goniometric devices are necessary. Even then manipulation noise and readout error make for less dependable results with high-energy tracks than the sagittal method.

† The expression $\bar{D}$ indicates a noise value obtained through taking second differences in Y, in the same manner as the mean scattering angle of a nuclear track is determined: $\bar{D} = 1/n \sum_{i=1}^n |D_i|$. ($D_i = Y_{i-2} - 2Y_{i-1} + Y_i + Y_{i+1} - 2Y_{i+2} + Y_{i+3}$).

A scattering stage is best calibrated for $\bar{D}$ noise with the aid of a Michelson or other type interferometer; one is usually supplied with the microscope so that the operator may verify stage performance before each measuring session. A certified straight-line ruling may also be used as discussed on p. 107.

a. The stage-drive mechanism must permit stepping-off of both constant and variable X-axis cell lengths with close-tolerance repetitive accuracy.

b. Y-ordinate increments are best measured in the optical system. The filar micrometer or other device used must be rigidly mounted in the eyetube against possible distortion introduced by the operator's hand: or, preferably, its operation should be by remote control.

c. The Z axis, or focus travel should have a noise level at least as low as that of the stage, since not only vertical measurements of track inclination are involved, but any noise in the Y direction can compound both the stage noise and the filar readout error.

d. Mechanical rotation facilities are essential for placing the track parallel to the stage travel; rotation about the optic axis is preferable, although this is a difficult design problem with large emulsion plates.

e. It is sometimes expedient to measure the vertical scattering of a track. In such case, it is of course important that the scattering stage have a low vertical noise level.

f. Operating efficiency calls for a more extensive X-stage travel than the two or three centimeters required for scattering a given track; it also requires some Y-coordinate stage travel for positioning purposes-- assuming, of course, that the inclusion of a system of ways for Y travel does not jeopardize the stability or accuracy of the main scattering stage. Operating efficiency depends more than is often realized on the convenient location of the instrument's operation and aligning controls, and upon adequate design provisions for the microscopist to sit comfortably before it during the exacting tedium of multiple scattering.

g. Additional features such as adequate throat capacity for a particular emulsion size; automatic cell-length programming; feasibility of adding digitizing equipment or special readout aids, etc.; should be considered when selecting a scattering microscope for specific emulsion programs.

With these points in mind, a brief survey of currently available scattering microscopes will be given.

a. The Koristka MS-2, made by the Fratteli Koristka Optical Co., Milan, Italy. This is the best-known and certainly one of the highest precision scattering microscopes to date. An X-axis stage with a D noise level of less than 0.02 microns is achieved by a unique design employing elastic deformation of compensating sets of steel "blades" supporting the emulsion table.* This low noise level is attained for 100-micron cell lengths; moreover,

* Parallel-blade-distortion stages are discussed on p. 86.

it remains fairly constant for cells up to 1000 microns. The drive unit provides a choice of several fixed and variable cell lengths, for a total continuous travel of 5 cm with vernier readings to 1-micron least unit of advance. A Y-axis travel of 5 cm is also provided; this unit has locking facilities for maximum stability during scattering measurements.

A similar compensating-blade system assures high linearity for the Z-coordinate movement. Here the only moving part is the objective; interchangeable binocular eyetubes, filar micrometer unit, goniometer, and Poohstrilino tube* are clamped rigidly to the microscope arm. This feature minimizes deflections from hand manipulation and will permit mounting of a digital-encoder unit weighing several pounds for direct mechanical hookup with the filar drum.

Two systems for emulsion-strip rotation about the optic axis are provided. One of these is a recently incorporated magnetic "spider" capable of handling heavy, outsized emulsion plates where the track to be scattered is far removed from the plate's center of gravity.

Additional features include magnetic clamping and reiterating facilities for the emulsion strip, low-positioned hydraulically operated focusing and a nearly horizontal projection angle for the various eyetubes to allow comfortable seating of the operator.

Possible inadequacies of this instrument include a limited throat depth of 6 in. nonstandard single-inversion optical system, limited substage optical adjustments, no remote control facilities for filar micrometer drive, and a somewhat restricted travel of the scattering stage.† Although not detrimental to "sagittal" method scattering measurements, this 5-cm travel follows a slightly curved rather than a linear path in the Z plane.

* See p. 32 for description of this optical-deviation-type micrometer.

† It is quite feasible to overcome two of these inadequacies - the limited throat capacity, and the lack of remote filar control, see Fig. 25, p. 123.

b. The Brower Scattering Microscope, built by William Brower,^{*} Orinda, California. The stage of this instrument is of the sliding-way type; massive, hand-lapped components with broad contact areas essentially float on a microfilm of oil. The $\bar{D}$ notes level for 100-micron or shorter cell lengths is approximately 0.02 microns. Some longer cell lengths do not hold as well as the Koristka; however, X-axis deviation from linearity in both the Y and Z directions remains near 0.1 micron for the full 3 in. of travel--an accuracy other scattering stages rarely hold through travels of half this distance.

On standard models[†] a Y travel of 1 inch is provided, as well as magnetic clamping for the emulsion plate and rotational facilities calibrated for readings to 0.01 degree.

The hydraulically controlled Z movement is mounted on unusually long ball-bearing ways for maximum actuating support of a conventional binocular-body system and the added weight of a hydraulically driven filar micrometer unit. The Z noise is well within that of the main stage.

Special features include low-positioned operating controls for both focusing and filar-micrometer control, automatic programming facilities for any desired cell-length intervals, as well as manual control and direct 1-micron interval reading facilities for the X-axis drive. A full 9-in. throat depth and massive construction throughout permit adequate handling of both extremely heavy and outsized emulsion plates.

Possible inadequacies are; readout for the filar-micrometer unit is subject to slight errors in reproducibility where either visual or digitized readouts are made from the remote actuating control. The bulk of the instrument makes for some inconvenience to short-torsoed operators. This can be considerably alleviated by substituting a greater-inclination binocular body for the 45-deg Leitz unit normally supplied.

c. The Zeiss-Jena Nuclear-Track Measuring Microscope, built by Carl Zeiss, Jena. Russia has had first chance at this new scattering microscope, but units are now available to the western world. Announced

* Mr. Brower was until recently head machinist for the University of California Physics Department. While there, he designed and built many measuring instruments for various nuclear research programs. These ranged from small two-coordinate measuring stages (prototypes of the compact stage described in Section III-C-2, p. 42) to scattering microscopes and ruling engines. Heading his own company, Mr. Brower now concentrates on manufacturing his scattering microscope and custom measuring stages for various research centers.

† Special models with up to 9 inches travel of the scattering stage, and 3 inches Y travel have been built. Few Brower microscopes are identical production models, since custom features requested by the purchaser are frequently accommodated.

performance is as follows: scattering stage--travel 55 mm; noise level for 100-micron cells, less than 0.01 micron; focusing noise of equivalent accuracy, with 0.1-micron direct Z readout.

The device for Y-direction scattering measurements is an optical-micrometer system similar to the Poohstrilino tube, with accuracy of reading to 0.02 micron.

Special features include complete thermal shielding, with the emulsion plate and all working parts fully housed inside the instrument. Subjective readout errors are controlled by an ingenious system which blanks out the image in one eyetube and superimposes the readout scales. Measurements may be read aloud into a microphone and tape-recorder unit built into the instrument. Special low magnification, high-aperture objectives are used, e. g. a 50x monochromatic measuring objective NA 1.35, with 600 microns working distance.

Possible inadequacies include: Y-axis stage movement, and limited emulsion-plate sizes--about 4x6 in. maximum for complete scanning. A further deterrent to wide acceptance of this instrument may well be its price-- \$30,000.

B. General-Purpose Emulsion Microscopes

1. The Koristka R-4

This is the only commercial instrument designed specifically for general emulsion analysis. Its features include a two-coordinate stage of 10-cm X travel and 5-cm Y travel with reading facilities to 1 micron on an X superstage of 2.5-cm travel. The main stage, riding on point contacts with cylindrical ways, is adequate for range measuring and for scattering to low Bev levels. The 8-in. throat and special optical-axis rotating facilities permit handling of emulsion plates to 12x12 in. Several features of the M-2 Koristka are incorporated: magnetic plate clamping and reiterating, low-positioned hydraulic Z control, Poohstrilino tube and other optical measuring accessories.

Possible inadequacies include restricted readout travels and related digitizing problems.

2. The Leitz Ortholux Universal Microscope (Model UAM)

This can now be outfitted as a serviceable large-plate scanning and scattering instrument with the addition of a stage of unique design.* A "pendulum" double objective and related optical devices function integrally with the stage to accomplish the following: direct linear readings (rather than rotational increments of a lead-screw dial) are given in better than 5-micron least

* This is the "Stodiek stage." The prototype was developed in 1955 by W. Stodiek at the Max Planck Institute of Physics.

units for a full 12 cm of X travel; Y noise of the stage is reduced to $1/100$ of its normal effect on field-of-view measurements. The 100x main component of the objective observes the specimen while spring-loaded against a 150-mm-long optical flat bridged above the emulsion plate and moving with it along the X travel. Thus, the objective actually "follows" minute Y deflections rather than magnifying them 100 times, as a standard objective would. The optical flat serves also as a linear scale. Rulings are inscribed along the full length of its reverse side. A 10x objective component mounted in the same housing with, but at right angles to, the main objective remains constantly focused on the scale and superimposes the positional readings on the specimen image in the eyepiece. Facilities for a 1-cm Y travel and for limited plate rotation are specially bridged above the emulsion so that tracks may be aligned without affecting spacing between optical flat and objective.

Additional optical components for the UAM instrument include a special condenser and objective, designed so that the emulsion can be clamped between them for rotation about the optical axis, and a Clausen optical-deviation micrometer (similar to the Poohstrilino tube.)

Possible inadequacies are: the Y travel is limited and also moves the emulsion strip by sliding rather than transporting it; there is danger of excessive wear in the Ortholux fine-focus unit which must support the considerable weight of this special stage. Rack-and-pinion drives and stage focusing seem to rule out attaching of cell-length programming facilities, automatic drives, or automatic readout devices for the stage. On the other hand, the fixed overhead optics assure adequate support for direct mounting of filar digitizers, photomultiplier units, camera equipment, etc.

3. The Cooke Universal Microscope (M4000 series)

These instruments have been widely used for both general analysis and multiple scattering by groups concentrating on small emulsion sizes. Model M4005 is equipped with a special two-coordinate ball-bearing stage. Precision micrometer-head drives read to 2-micron least units for the 2.5-cm travel of each coordinate. A rotating superstage (M4344) can be attached in several reiterating positions; it provides 5 cm of rapid positional travel as well as plate rotating facilities. Without considerable modification of the stage, a 2-X 4-in. emulsion size is the maximum which can be accommodated.

A recently improved low-positioned fine-focus mechanism provides excellent remote control for the nosepiece section of the above-stage optics. The binocular-body unit (or other interchangeable body tube types) remains fixed to the massive, reversed-design arm. This fine-focus arrangement permits both the mounting of comparatively heavy, extended travel stages,*

* A counterbalance device built into the stage-support bracket prevents the strain of heavy stage loads from affecting the course-focus mechanism. The L. R. L. large-plate measuring stage (described on p. 42) has been mounted on M4005 stands without undue strain on the course focus from its 17 to 18 pounds' weight.

and maximum support for heavy mechanical or optical devices attached directly to the binocular- (or trinocular) body tubes.

Possible inadequacies include a shallow throat capacity of about 4-5/8 in. (which the fine-focus mechanism makes difficult to extend). Vertical adjustments of the stage-actuating coarse focus complicate the use of any automatic stage driving or readout equipment too bulky to be accommodated on the stage platform itself.

V. CUSTOM-BUILT MICROSCOPE EQUIPMENT

Since the ramifications of emulsion microscopy extend well beyond the range of commercial "Universal" microscopes or even the Koristka R-4, much emulsion equipment continues to be custom-built. Normally instruments are independently developed at the several research centers for specific emulsion sizes and specialized, often unique, analysis procedures. Even among custom designs, no universal emulsion microscope has evolved. Rather, the net result is an impressive array of instruments and auxiliary devices, each of restricted application, but encompassing en toto the full gamut of current techniques.

A versatile, all-purpose emulsion microscope could then be realized by combining the most successful and pertinent features of custom instruments to date. A description of such a theoretical instrument may be of interest both as a composite survey of custom designing and to point out the engineering problems involved in equipment now required to handle the large emulsion sizes and exacting analysis techniques of high-energy research.

A. Specifications for a Universal Emulsion Microscope

1. Optical System

This will be an integral, peak-performance unit, not squeezed into available space, but forming the major component around which other units are to be fitted. Its construction will combine extreme mounting rigidity with finger-tip ease of selecting and aligning a full range of ocular, objective, and substage condenser combinations.

The light source, with its own full complement of aligning and selecting controls, is to be a precision component of the optical system. Its positioning must provide optimum performance without recourse to excessive light-path compensating devices, yet assure full thermal isolation from the microscope. Facilities for monochromatic, ultraviolet, and incident illumination will be included, with adequate intensities for projection and photomicrography.

2. Basic Stand

This will be of reversed design to permit massive structural rigidity of an arm with a full 28 in. of horizontal projection. The free end of this arm

must provide vibrationless support for the following units: trinocular body and multiobjective turret; coarse-and fine-focus mechanisms; mountings for goniometer, filar micrometer, auxiliary photomultiplier, and camera attachments, etc. Backlash and vibration-free operating linkages will run from these units back along the arm to convenient low-positioned control knobs and to automatic drive and readout equipment.

3. Mechanical Stage

Full versatility will require combining the features of the two-coordinate extended-travel scanning stages, indispensable for efficient preliminary analysis of large emulsion plates, and the measuring accuracies, rotating facilities and auxiliary devices of the best range-measuring and scattering microscopes. Coordinate motions of 6X9 in. will be provided. Maximum accumulative lead error and general noise deviations from true linearity for each traveling component must fall within 1.0 micron per centimeter. For high-energy scattering, a selected portion of the X travel will be precisely calibrated, and correction factors programmed into the automatic computing system to hold scattering noise below 0.01 micron for consecutive 100-micron cell lengths in this region.

Precision lead screws with both manual and variable-speed motor drive will actuate the travels. A servoresolver system and programming device will permit any predetermined movement pattern in the coordinate plane to be carried out automatically, from area scanning and track following to the stepping-off of cell lengths for scattering. Additional mechanisms will provide accurate rotation for any point in the emulsion strip about the optic axis and a tilting movement about this axis of the entire stage assembly so that inclined tracks with dip angles to at least 45 deg may be measured or photographed directly in the plane of their trajectory.

The stage table should have support and clamping facilities for emulsion plates of all dimensional combinations between 1X3 and 18X24 in. with provisions for rapid reiteration of the sizes beyond travel limits. A system for precise duplication of emulsion positions will permit adjacent pellicles from the same stack exposure to fall immediately into close register for the following-through of inclined tracks.

4. Measuring Facilities

Calibrated dials and scales will be included for convenience in positioning and classifying of material, but all actual measuring procedures will utilize analog-to-digital converter units attached to stage-coordinate and rotation drives, to the fine-focus or Z coordinate drive, and to goniometer and filar-micrometer units. The flick of a foot switch records on electronic-computer tape any combination of spatial measurements desired for each track grain or event the operator sets to his crosshairs. Coordinate positions read to seven figures in 0.1-micron least intervals; stage rotation and goniometer angles to 0.01 deg; filar or Poochstrilino micrometer to a possible 0.01-micron least reading.

5. Auxiliary Equipment

This will include photomultiplier scanners for automatic density and counting procedures, photomicrographic equipment, visual and televised projection apparatus. These and any additional specialized devices will be designed for rapid mounting and removal so as not to compromise the ultimate objective--a compact instrument before which the microscopist can sit comfortably, with ample leg room, and with all controls as easy to reach and to manipulate as those of a conventional laboratory microscope.

Operational custom prototypes whose features have been incorporated in this theoretical microscope will be listed and briefly discussed in the Section following.

B. Custom Prototypes of Special Interest

1. A Precision Microscope for Large Nuclear Plates

Developed jointly by Brookhaven National Laboratory and the University of Chicago Department of Physics, this instrument incorporates a massive reversed stand of 12-in. throat capacity and a precision stage of greatly extended two-coordinate travel. Superimposed dovetail ways permit continuous lead-screw actuated travels of 21 by 15 cm (8-1/4 by 6 in.). $\bar{D}$ noise for 1000-micron cells remains below 0.03 micron over an 8-cm central portion of the X travel. A description, with drawings of the dovetail slide construction is given by G. T. Zorn et al.⁸

2. A Revolving and Tilting-Stage Microscope

This instrument was developed at the Nobel Institute of Physics, Stockholm, Sweden. A Leitz Ortholux microscope has been fitted with a custom stage of interesting potentialities. (The stage is frequently referred to as the Slatis stage.) In addition to positioning travels and rotation about the optical axis in the conventional coordinate plane, there are provisions for precise tilting of the entire stage about a horizontal axis. Thus, tracks of moderate dip angle* may be directly studied or photographed in the plane of their trajectory.⁹

3. A Large-Plate Scanning Microscope with Hydraulic Stage

Developed at the University of California, Department of Physics, Berkeley, this is a reversed-stand instrument of 11-in. throat capacity. The hydraulically actuated stage provides travels of 9x3 inches. Flow valves, capable of discrete manipulation, permit a wide variation of travel rates along either axis. Moreover, X and Y rates may be combined for movement along any resultant angle in the plane, or for "steering" among star prongs or curving trajectories.

* Conventional optics restrict the tilt to about 20 deg max. Special objectives which would permit observations in the plane of very steep tracks (to 75 deg) are discussed by W. J. Bates and others.¹⁰

4. A Measuring Microscope for 18X24-Inch Emulsion Plates

Developed by William Brower for the University of Tennessee, Department of Physics, this 650-pound instrument (Fig. 10) provides a full 28-in. throat capacity through use of a welded-steel arm of "boxed in" construction. A single coordinate stage utilizes broad-contact sliding ways to achieve high measuring precision. Total deviation from linearity holds within 0.1 micron for 3 inches of travel. Maximum stability of the measuring stage is unaffected by a Y-positioning travel built into the arm and optical assembly. Fine-focus and filar-micrometer units are hydraulically remote controlled.

5. A Digitized Range-Measuring Microscope (Fig. 11)

Developed at the Lawrence Radiation Laboratory, Berkeley, this reversed-stand design utilizes a buttressing arrangement of two heavy arm components to provide adequate rigidity for a 13-in. throat depth, and to permit locating a high-intensity light source between the separated lower extremities of the arms. A low-positioned fine-focus control actuates both the above-stage optics and a 1000-count-per-revolution digital encoder. Similar encoder units giving 1000 counts per revolution for 100 revolutions are attached to the stage lead screws. The stage is a base-mounted version of the L. R. L. large-plate scanning stage described on p. 42. Travels have been restricted to just under 10 cm by 10 cm (i. e., 100 revolutions of the 1-mm-pitch screws) so that the capacity of the encoders will not be overshot. Thus, 1-micron least-interval X, Y, and Z readouts are algebraically continuous throughout a 100-cm² coverage of emulsion. Suitable electronic circuits permit positional data from the encoders to be recorded on IBM cards, along with emulsion-shrinkage factors and all necessary indicative information for automatic computer programming. The microscope and its related electronic equipment are discussed by W. H. Barkas;¹¹ mechanical details, including digitization problems, are discussed by J. C. Hodges.¹²

6. A Semiautomatic Multiple-Scattering Microscope

This microscope (Fig. 12) was developed by the University of California, Department of Physics, Berkeley. Built specifically for very large emulsion plates, this instrument incorporates a massive scattering stage having 9 in. of travel. The moving component of the stage alone weighs over 100 pounds, yet it glides easily on an oil film between broad way surfaces. Its lead-screw drive is motorized and connected with a programming device which permits automatic advance in any sequence of fixed or variable cell lengths determined by perforated tapes. A 3-in. Y travel is achieved by mounting the entire microscope arm and optical assembly on a set of dovetail ways. Fine-focus and filar-micrometer settings are both hydraulically controlled from remote operating knobs. In addition, the filar control screw is coupled to a Giannini digital encoder. Output is fed to a Frieden automatic adding machine programmed to take first and second differences of the Y scattering increments.¹¹

7. An Automatic Scanning Microscope

Developed at the University of Rome, Physics Institute, this is perhaps the best example to date of a fully automatic scanning device.

ZN-2437

Fig. 10. A measuring microscope for 18×24-in. emulsion plates, built by William Brower for the University of Tennessee.

ZN-2441

Fig. 11. Range-measuring microscope with digitized X, Y, and Y measuring coordinates, developed at L.R.L., Berkeley:

(a) side view; (b) rear view, showing buttressing arrangement of the two arm components and location of the illuminator. Also visible is a portion of the cable-and-sheave drive used to extend fine-focus control to a convenient operating position and to a convenient location for attaching a Z-axis digitizing encoder.

ZN-2442

ZN-2034

Fig. 12. A semiautomatic multiple-scattering microscope built by the Department of Physics, University of California, Berkeley.

The observer's eye is replaced by three light pipes, each leading to a photomultiplier unit. These are mounted integrally with a diaphragm slit in the image plane and with a mechanism for rotating the whole assembly in 1-deg steps about the optical axis. The microscope stage is driven in the Y direction by a hydraulic piston, automatically actuated to give 3-cm periodic traverses. After each to-and-for traverse, the vertical focus is automatically changed by 8 microns; when the lower surface of the emulsion is reached, the fine focus is returned, the slit rotated by 1 deg, and the scanning sequence repeated. ~~Electronic circuits sort two-fold from three-fold~~ coincidence of the photomultiplier outputs as a passing track lies either approximately or precisely aligned with the slit. From scaler data for each run and the total for each angular position of the slit, the angular distribution of tracks in the emulsion is readily determined. Range distribution of tracks may be similarly determined by replacing angular rotation of the slit with small intervals of X-stage coordinate advance. Distribution patterns are consistent with data obtained by visual scanning and can be obtained up to 100 times more quickly. As yet the device has been successfully proved only on thin (50-micron) emulsions with relatively low background.¹³

C. Problems in Custom Designing

Microscopes of excellent mechanical fabrication can be found gathering dust at various research centers. Some may be over-specialized devices made obsolete by changing analysis techniques. Some are white elephants, never efficiently used because of inadequate attention to two basic design problems: fitting in the optics, and fitting in the operator.

1. Fitting-in the Optics

Where comparable optical components are used, the resolution, contrast, and over-all image quality from a custom instrument should certainly equal that of a well aligned conventional microscope. If not, the fault must lie with the only remaining variable--the spatial relationship between individual optical components. Over-extension of the optical path between light source and condenser is a common error. More insidious are slight individual component misalignments with respect to the optical axis of the objective or to the axis through the lens elements of the substage condenser. These problems will be briefly discussed.

Locating a light source at its most efficient operating distance often entails radical design concessions to accommodate the unit's bulk, assure its thermal isolation, and provide access to its aligning and filter controls. In such cases, extending the light path is certainly advisable. The poor results sometimes obtained can be traced to either an initially inadequate illuminator or to incorrectly computed or poor quality auxiliary lenses inserted along the light path. Suitable illuminator types (discussed on pp. 21-22) are best modified for short extensions of 3 or 4 in. by replacing the field lens with a similar type of longer focal length. Such lenses are often available from the manufacturer of the illuminator.

Greater extensions, up to at least 30 in. of total light path, * can be realized by inserting a fully color-corrected projection lens of proper focal length and adequate diameter immediately in front of the illuminator. Whatever the method used, the designer should verify that at its proposed location the light source

- a. delivers a well collimated beam of ample cross section to fill the substage condenser,
- b. retains the true geometry of Koehler illumination,
- c. supplies adequate light intensity for maximum emulsion opacities and to permit use of recommended filters and diffusing screen,
- d. can be thermally insulated from critical microscope components,
- e. is easily accessible to the operator for fine-centering adjustments and filter selection.

The designer intimately familiar with emulsion microscopy can best appreciate the problem of fitting separate optical components to a fabricated stand. For thin biological slides, optimum alignment need only occur in the immediate vicinity of a fixed specimen level. In thick photographic emulsions it is essential that the objective remain in precise optical alignment at any point along a vertical gradient of from 300 to perhaps 500 microns. Deviations not only reduce image quality and insert measuring inaccuracies, but are immediately detectable by the operator as irritating angular shifts of each event and background grain coming into or going out of focus during vertical scanning.

Essential mounting requirements are:

- a. proper relative heights of the surfaces provided for bolting on the overhead optics and the substage condenser components. This should assure, when the objective is lowered to approximate contact with the emulsion plate, and the condenser raised to approximate contact with the plate's under-surface, that the ways for both the overhead course-focus mechanism and those for the condenser rack-and-pinion unit are not over-extended, i. e., that at this optimum working position the fixed- and sliding-way members are in a region of maximum contact with each other, and can provide maximum stability to the optical components they support.

* The 28-in. throat microscope of the University of Tennessee uses an AO Ortho-illuminator and a two-element fully corrected auxiliary lens for the 30-in. spacing between its condenser and light source. Both quality and intensity range are adequate for thick emulsions.

(On this, as well as several other custom designs employing the popular Ortho-illuminator, the neck extension housing the first-surface mirror is sawed off and placed beneath the substage condenser.)

b. The linear travels of the course-focus unit, the fine-focus movement, and of the substage condenser focusing unit must be mutually parallel.

c. The optical axis through the objective's lens elements and that through the condenser must coincide, and this common axis must in turn be parallel in both vertical planes to the line of travel of the focusing mounts.

d. The common optical axis should be perpendicular within a fraction of a degree to the plane of the emulsion table and that of the coordinate stage travels.

Some aids that have been found useful in fitting and aligning optical assemblies might be listed:

a. On small custom instruments an "easy way out" is to utilize intact that portion of a conventional stand which includes the mountings for **both** above-stage and substage optics. For example, the arm of inclination joint laboratory microscopes (described on p. 35) can often be directly built into an instrument of either standard or reversed-stand design. Even where spacer blocks are inserted to increase throat capacity, realignment of the optical path is normally required in only one plane.

b. Where a fabricated arm unit is essential, it should be designed to accept a course- and fine-focus unit of commercial manufacture for the overhead optics and a standard rack-and-pinion condenser mount. Not only is extensive precision-machining and -gearing avoided, but the "feel" of conventional units (especially the rack-and-pinion course adjustments) allows the operator his customary finesse in racking rapidly down with the objective or upward with the condenser to within a hair's breadth of optimum focus. These units may be amputated from high quality conventional microscopes (Fig. 13), or in some cases, purchased separately. Purchasable focusing units or "limbs" include the Leitz course-and-fine limb (code: CUELOT) adaptable to reversed-type arms and provided with a dovetail to take Leitz Ortholux binocular bodies and nosepiece units; the B&L Dynoptic course-and-fine limb assembly (B&L factory assembly no. 127ND) contains no fine-focus actuating screw but is nicely adaptable to remote control through hydraulic or other linear actuating devices. The well built B&L Dynoptic or research substage assemblies may also be purchased as separate units.

c. Coarse-and-fine limbs and substage units are best provided with adapter plates. These are bolted to the microscope stand by means of easily accessible machine screws running through oversized clearance holes. Thus, with the addition of push screws or shimming, the components can be shifted in all three planes during preliminary adjustments. Mechanical alignment to extremely close tolerances can be achieved with jigs fabricated to reproduce an axial line through the center of the nosepiece orifice and that of the substage-condenser mounting ring. Deviations in colinearity of the focusing ways can then be detected as each component is racked up and down; this procedure can be duplicated with stopped-down optics producing a fine pencil of light. Before dowel-pinning components, a final check should be run with emulsion-plate and standard optics. A series of objectives should be interchanged to verify that the substage condenser is sufficiently centered in the horizontal plane to permit its centering screws to take care of objective axis deviations.

ZN-2443

Fig. 13. Experimental emulsion microscope showing the following design features: (1) use of a coarse-and-fine unit "amputated" from a standard Leitz laboratory microscope (model B) and an early-model Leitz binocular body fitted for either conventional or reverse mounting; (2) use of a dental-machine belt drive (see p. 66) to extend fine-focus control to a convenient operating position.

d. Fitting-in the substage condenser invariably conflicts with optimum structural arrangement of large mechanical stages. This problem will be further discussed under "Mechanical Stage Design;" however, it should be stressed here that arrangement of the microscope's stand and stage components must permit easy access of the operator's hand to the condenser centering screws, iris diaphragm handle, rack-and-pinion knob, and to facilities for mechanically or manually adjusting the substage mirror. Remote controls for these adjustments are costly and efficiency-reducing alternatives.

2. Fitting-in the Operator

This is normally a minor problem where dimensions of the custom instrument can be made to approximate those of commercial laboratory microscopes. Main points of concern are convenience features such as location of actuating controls and easy-to-read dials and linear scales.

Such dimensional similarity can rarely be held where a design specifies throat capacities and extended-travel stages adequate for current high-energy emulsion sizes. Often the only resemblance to a laboratory microscope is a protruding binocular body. Considerable sacrifice in optimum structural design may be necessary if this binocular body is to protrude far enough or remain within height tolerances which permit comfortable viewing by a seated operator.

These and all other possible concessions are justified when an instrument is to see continuous and efficient use in a program employing scanning personnel. Table-top-to-eyepiece height must be fitted to the average feminine torso. Controls must have low enough torque and be located conveniently enough so that a scanner with average muscular attributes can operate them continuously for four to six hours. The need for accessible condenser and light-source adjusting facilities was mentioned in the preceding section. The scanner makes many minor adjustments of condenser diaphragm and height, light intensity, filters, etc. during a day's scanning session, as well as occasional major alignments. Inadequate or poorly located controls can easily extend a few minutes of routine manipulation into several hours of exasperating alignment endeavor.

A custom device intended for intermittent use by the physicist himself, or for complex, nonroutine analysis procedures often warrants some sacrifice of operator convenience to functional precision, or again, to reduce excessive fabrication expense. For example, the precision of stages with directly superimposed way units -- such as the Brookhaven-Chicago design described on p. 55 -- will exceed that of comparable coordinate travels built around a substage condenser. The penalty is an increase of 6 to 8 in. in the over-all height of the microscope; eyepieces are therefore placed well beyond the physical limitations of most seated operators. Again, geared, hydraulic, or other systems for extending manual controls to within comfortable reach may require as much design time and fabricating expense as the entire remainder of the microscope.

Where choice is up to the designer, he should carefully weigh the possible consequences of inadequately fitting-in the operator. An instrument originally intended for a certain mechanically adept and muscular physicist, or for occasional precise measuring routines, is often pressed into more general service by expanding emulsion programs. If it cannot be feasibly modified for efficient use by scanning personnel, the "monster" * will soon be gathering dust with other white elephants.

3. The Deep-Throat Microscope Arm

A reversed-stand construction is essential for microscopes of much over 5-in. throat capacity. The arm is usually a single-unit fabrication with a flared lower extremity for broad surface contact when bolted to the instrument's baseplate. After rising vertically to above the level of the stage platform, it projects towards the operator. When necessary, its free end should also be flared to provide ample surface area in a precise vertical plane for bolting on the focusing limb and optical components. An artistically pleasing as well as structurally sound arm is easily fabricated from 2-in. or thicker aluminum alloy plate. Brass or aluminum castings are often used when several similar units are planned.

The span achieved between objective lens and the vertical portion of the arm is of course, the throat capacity of the instrument. Throat depths of 9 or 10 in. offer little difficulty when the arm is provided with a broad footing and retains sufficient cross section area during its vertical rise and forward extension. The test is that free end support some 3 to 5 pounds of focusing and optical components† without sagging or flexing when operating controls are handled. Stability of the arm under 1500x or higher magnification should be ascertained; stresses in other planes than the vertical are introduced by viscous-immersion-oil drag between the objective and a moving emulsion plate. These seemingly insignificant forces and others such as convection currents from the light source or ambient-temperature fluctuations become increasingly important as arm extensions are increased. Special structural designs which have achieved throat depths up to 28 in. are mentioned in the preceding section (pp. 55-56).

* The writer can assure builders of custom equipment that it is no rarity to find one's somewhat cumbersome though mechanically adequate instruments tagged "Monster," "Armstretcher," "Frankenstein Junior," etc. by disgruntled scanners.

† This is a modest estimate. Photomultiplier units, plate-rotating devices, digital encoders, camera equipment, etc., often place an additional several pounds burden on the arm extremity. It is sometimes expedient to considerably over-design the microscope arm in anticipation of future needs.

The following peculiarity of reversed-stand instruments should be considered: emulsion plates larger than approximately 6x6 in. demand that the entire emulsion area project away from the operator if peripheral regions are to be conveniently studied. Thus, the arm projection should exceed the longest dimension of the plate. Where procedures call for plate rotation or for aligning any given track with a stage-coordinate travel, throat capacity will only be fully adequate when it equals the diagonal of the largest plate size to be used.

4. Remote Actuating Controls for Overhead Optics

A low-positioned control of the fine-focus unit is essential on microscopes intended for high-efficiency scanning, or prolonged observations. Remote control of the goniometer, filar micrometer, or other measuring device normally manipulated at eyetube height may also be advantageous in certain analysis procedures. Custom microscopes require precision fabrication and hand-fitting of each remote actuating device. Much effort is sometimes spent in trying and discarding various remote control systems before an adequate solution for a particular microscope is found. The following suggestions, gleaned from such trial-and-error approaches and from careful analysis of successful devices, may be helpful:

a. General considerations:

1. Provisions should be made in the microscope's layout and especially in the design of the arm unit for accommodating a specific, experimentally proved control device.
2. The fine-focus control should not merely be lowered but precisely positioned to permit comfortable resting of the operator's arm, and a minimum shifting of fingers to reach a stage drive or other control which must be operated with the same hand.
3. Control extensions should retain the same feel with regard to torque, backlash, and travel-per-turn as that of conventional units.

b. Evaluation of specific remote control devices:

1. Hydraulic systems: A pair of piston-fitted cylinders, or metal bellows (sylphons) separated by any desired length of small-diameter tubing offers the smoothest operating and least cluttered mechanism for remote control. Rotational input is easily achieved by a fine micrometer lead screw. Rotational output is rarely attempted. This means that most conventional fine-focus limbs must be modified; or special units precision-fabricated. The same problem requires the fabrication of special filar-micrometer units if these are to be hydraulically actuated. The use of this system for remote goniometer settings does not seem feasible.

Special hydraulic fluids must be used; moreover, the problem of removing the last vestige of trapped air bubbles has never been solved. Usually mushiness -- often more irritating to be operator than gear backlash -- can be reduced to a point where it does not affect manual focusing efficiency. However, few hydraulic units achieve sufficient positive control

to permit accurate readout drums or digitizing equipment to be attached to the driving unit.

2. Servo systems: Paired self-synchronous motor units requiring only an electrical link between microscope baseplate and the arm extremity and giving one-to-one rotational output for rotational input might seem an ideal means of extending controls. Unfortunately, the best of these units currently available, even when fitted with elaborate electronic damping circuits to minimize "hunting" of the receiver armature, give only modest rotational accuracies.

Vibration and hum of a heavy synchro receiver may be transferred to optical components mounted adjacent to it on a long arm extension. Even where a servo-system has been electronically stabilized, the operator is restricted to cautious movements of the fine focus. Rapid spins, frequently used in vertical scanning or for a quick descent to take grid readings, can easily throw the transmitter and receiver units 360 deg out of phase.

3. Drum-wound cable systems: Excellent remote control is obtained through use of a fine multistrand steel cable and appropriate pulleys. A small V-groove pulley wheel is attached, or preferably connected through a set of antibacklash spur gears, to the fine-focus knob, filar micrometer, or goniometer. The cable is looped over this and then led back along the arm and down to operating position by idler pulleys. Each cable end is wrapped several times in opposite direction around a comparatively large-diameter drum pulley or sheave and secured to this. (See Figs. 11 and 26, pp. 58b, 126.)

If correct ratios are chosen, a few turns of the sheave move the focusing or filar unit through its full range of 20 to 30 turns. The otherwise impossible problem of a knotted cable belt is solved, and as long as proper tension is maintained through a spring-loaded idler, the cable drive is positive and backlash free. Installations of this type have proved quite trouble-free and fully adequate for visual readouts or digital-encoder connections at the remote driving end.

4. Endless-belt systems: Seamless rubber belts (of the O - ring type) and cloth dental-machine belts are perhaps the only belt types which offer a smooth enough seam for running over pulley surfaces along the microscope arm without occasioning distortion bumps in the optical system. Rubber belting is rarely used owing to excessive creep and lag. Dental belts, available with some choice of lengths, give much more positive action. they are often adequate for a comparatively short extension of focus or filar control, providing readout facilities need not be attached to the driving member. (See Fig. 13, p. 63.)

5. Gear systems: Long sections of shafting fitted with matched mitre gears can be used to bring actuating controls down from the microscope arm in right-angle steps. Extreme care must be taken in aligning shaft-bearing hangers and in correct settings of gear mesh. When precision fine-pitch gears, accurately ground shafting, and precision ball bearings under a slight preload are used throughout, geared extensions provide a positive, low-torque solution for remote control.

Backlash cannot be entirely eliminated,^{*} but it will be present as a minute constant increment of rotation noticeable only when the knob is reversed. This is less disconcerting to the operator, and more readily compensated for in readout systems than the creep or "mushiness" of certain other systems.

6. Flexible shafting: Little need be said about this often-tried and always disappointing means of control extension. Speedometer-cable-type shafting should be reserved for infrequently used aligning controls which cannot be expediently extended by other means.

5. Rotation About the Optical Axis

Where only one stage axis is to be used as a measuring coordinate, the particle track must be positioned along that line of stage travel. An operator can readily determine the degrees of angular misalignment of a selected track slanting across his microscope's field of view. It is not difficult to construct a device for turning the emulsion plate through a specified arc. However, the utility of such a device depends on whether the operator can find his selected track again after the rotating maneuver. The only certain assurance is a device which rotates the track about a point that always remains within the limits of the field of view. At a normal 1000x magnification, this requires a center of rotation located within a radius of about 0.005 in. of the optical axis through the objective. Rotating systems of this type are built integrally with the basic stand and optical system, rather than into the stage components.

Some form of open-center turntable is universally employed.[†] The fixed member of this is fitted with centering screws where it attaches to the microscope stand or optical mounts. These screws permit fine adjustments after installation, especially recenterings for axial differences of interchanged objectives. The rotating member must have a precision, low-friction contact surface with its mate. It must also be provided with a positive means for clamping and supporting an emulsion plate whose center of gravity may be well removed from the clamping region.

* Recently available antibacklash mitre gears have proved disappointing for most microscope applications. A definite roughness of mesh is readily transmitted to the arm and the optical system. This roughness is much more pronounced than that of antibacklash spur gears, which are often successfully used on devices in direct contact with optical components.

† It should be noted that while conventional laboratory microscope stages have long provided accurate optical axis rotation by means of a turntable stage mount, the rotation in this case merely facilitates angular measurements; it does not permit the turning of some linear contour in the specimen so that it is parallel to a coordinate of stage travel.

The turntable assembly must either be attached to, or contain in its own construction, sturdy facilities for a short vertical travel since it must lift the emulsion plate and hold it free of the stage top during rotation. (The need for breaking contact between the emulsion and the stage table introduces additional problems of building some sort of clamping device--magnetic or vacuum chucks are often used--into a stage superplate so that the emulsion can be quickly released, and after rotation clamped again in whatever position its long and short dimensions are newly orientated.)

The following optical-axis plate-rotating designs have proved successful with emulsion strips to a nominal maximum size of 4x6 inches:

a. The turntable is fitted directly to the sleeve of an appropriate microscope objective. A bayonet nosepiece fixture is used. The standard centering screws of the bayonet mount are often sufficient to align the whole assembly with the main optical axis. A vacuum groove, machined into the rotating member, with a flexible hose connection to a vacuum supply clamps the emulsion plate during rotation. Lifting facilities are of course provided by the microscope's focusing units.

Limitations: This device is not applicable to short-working-distance objectives. The track cannot normally be observed during rotation; thus, a degree-graduated turntable is necessary. Since vacuum contact is with the actual emulsion surface, processing bubbles, scratches, etc. near the desired point of rotation can cause vacuum failure.

b. The turntable is fitted directly to the sleeve of the substage condenser. Here the fixed member is best provided with a set of centering screws which function separately from those of the condenser mount. The rotating member normally has a machined groove connected by a flexible line to a vacuum system. The condenser's rack-and-pinion focusing mount provides plate-lifting facilities.

A rotator of this type, with small permanent magnets used to clamp the emulsion plate to the turntable instead of a vacuum system, is discussed and illustrated by A. E. Dyson et al.¹⁴

Limitations: Two separate maneuvers are required: the objective must first be racked up to clear, and then the condenser focus actuated to lift the emulsion plate. However, the objective may be refocused and the track observed while in rotation, obviating need for a graduated turntable where substage positioning would present reading difficulties. Such a device will add considerably to the diameter of the substage clearance to be allowed for in the design of stage way assemblies and superplate window cutouts (discussed in the section following).

c. A turntable built around, but fully separate from, the substage condenser offers greater stability, since it can be base-mounted rather than supported through the substage rack-and-pinion ways and an offset condenser mount. It also permits the rotator to be raised and lowered without affecting some optimum condenser position. A separate lifting device must of course be built into the turntable mount.

Limitations: An even bulkier substage assembly must be allowed for, unless some special small-diameter condenser barrel and special elevating systems for both units are combined. (The Koristka MS-2 has by this means achieved a very compact plate-rotating turntable. The portion of the rotating sleeve which projects through the superplate window, is about 1 in. o.d.)

d. Two turntables may be used, one attached to the condenser and one to the objective. The emulsion plate is clamped and held securely between these as the condenser is elevated. Such a device is also described by Dyson et al.¹⁴

Limitations: This arrangement normally precludes observations of the track during rotation. A similar system, used on the new Leitz scattering stage, does permit refocusing on the track through use of a spring-pressure device built into a special low-power objective. However, this indicates an objective switching maneuver before and after each rotation.

Additional limitations are common to all the above rotating systems: The major one is of course that of plate size. There is the problem of very small plate sizes (1X3, 2X3, or even 2X4) falling through the superplate cutout. Plates measuring 1X3 in. are often too narrow for the spread of a vacuum-ring groove. More critical is the problem of sizes larger than 4X6 in. Such plates (or even a 6-in. length grasped near one corner) exert dangerous stress on optical mountings and fine-focus way systems. The emulsion plate itself may not stand such overhang as required for rotating about a selected track near one corner of a 6X9 pelicle. The normally used 1-1/2 mm-thick glass backing will frequently break under the strain. A larger-diameter contact surface of the turntable rotor would lessen this problem, yet this adds to another limitation of the above devices: Tracks near the perimeter of the pelicle must be excluded from rotation since a portion of the vacuum groove will lie off the plate. The radius to the outer rim of the turntable rotator will be the minimum excluded border thickness around the plate. [The system described under (d) will be an exception to this, since it does not require a vacuum cup. This possibly is also the only rotator which can be used with 1X3 slides.]

The above difficulties are best overcome on larger emulsion sizes by the seemingly simple expedient of using two or more vacuum cups attached through offset arms to an optical-axis-centered turntable. Two such devices will be described:

a. Certain MS-2 and R-4 Koristka microscopes provide, in addition to a substage-mounted optical-axis rotator, an overhead turntable. Projecting from this are four "spider legs." These are adjustable both vertically and horizontally; their free extremities contain small vacuum cups (some models are provided with magnetic grasping discs). Plates as large as 9X12 can be held with the cups distributed around the center of gravity. This means that a track on the very perimeter of the plate may be axially rotated (within the limits of the microscope arm) while the supporting legs remain distributed well to one side of the objective and over the central region of the plate itself. The turntable is graduated in degrees and includes a micrometer adjustment for precision final settings. The writer has not

been able to ascertain whether the turntable is attached to the microscope arm or to the objective mount. It may be noted that a rotator of this type would be extremely difficult to fit around above-stage optics of more conventional design than those of the Koristka--especially where it is desirable to retain a revolving nosepiece.

b. A multiple vacuum-cup rotator (similar in principle to the above is under development at the Lawrence Radiation Laboratory. Maximum stability for moving heavy metal-framed 6X9 and 9X12 emulsion plates through extensive rotational angles has been stressed. The large turntable (14 in. in diameter) is centered to the optical axis and held above the stage superplate by three offset legs. Two of these have base-mounted supports; a third, located at the rear of the stage area, projects downward from the reversed-design microscope arm. This allows large emulsion sizes free swing into the full extent of the microscope throat.

The vacuum cups are strategically located within the 12-in. opening of the turntable, so that for any emulsion position, the turntable rotor may be revolved until a minimum of two cups lie directly over areas of equal weight distribution. Thus, in normal operation, no adjusting or other manipulation of individual vacuum cups is required. A lever lowers the entire turntable until the cups make contact with the emulsion surface. A linkage at this point is being considered, so that as the plate is lifted the objective lens automatically racks up to clear.

A "bonus feature" of optical-axis rotators, especially those capable of handling large emulsion sizes, might be mentioned: They provide an excellent means for plate reiteration. While the emulsion plate is held free of the stage, a coordinate travel which has reached its limit may be returned, so that the full extent of movement is again available when the emulsion plate is reclamped to the superplate. This process may be repeated indefinitely.

D. Design and Fabrication of Mechanical Stages

The mechanical stage is frequently the most intricate and specialized component of emulsion microscopes. Inadequacies of commercial equipment force many emulsion groups to custom-build most or all of their microscope stages. Such an undertaking calls for a mechanical designer familiar with emulsion microscopy. It also presupposes precision machining facilities, and a supporting group of instrument technicians adept at precise hand-fitting and "lapping-in" procedures. Special measuring equipment is necessary for lead-screw calibration and for determining stage noise and other performance characteristics.

1. Preliminary Considerations

An analysis of custom-stage building should differentiate between two general groupings: base-mounted stages, and stand-attachable stages. "Stand attachable" will be used hereafter to designate assemblies specifically arranged for direct attaching to a standard microscope stand (recommended stands were discussed in Section II.) "Base mounted" will designate all

stages whose fixed components are either designed for bolting to the base, or are actually built into the base, of fabricated microscopes such as discussed immediately above under heading "C."

Base mounting seems essential for multiple-scattering and other measuring stages demanding maximum precision and stability. It is also necessary, of course, where the designer cannot fit specifications for travel extent, mechanized drives, readout facilities, etc., into a stage compact enough for conventional stand mounting.

The stand-attachable stage must be carefully restricted both as to component layout and weight. Perhaps for this reason builders of custom equipment too often overlook its potentialities. Attachable custom designs suitable for the large emulsion sizes are extremely rare. The Lawrence Radiation Laboratory's large-plate scanning and measuring stage (described on p. 42) remains an almost isolated example in this field. However, designs such as this can attain travels to 5X5 in., measuring accuracies sufficient for most analysis procedures save that of multiple scattering, and can efficiently handle emulsion sizes to 6X9 in. (or even to 9X12 in. when mounted on conventional stands of greater than normal throat depth).

Basic scanning routines, especially, call for a stand-attachable design. The average scanning technician seems more efficiently at home with a familiar laboratory microscope. Moreover, relative costs and fabrication facilities normally rule out fully custom-built microscopes. For example, programs concerned with large emulsion volumes often require as many as ten or twelve instruments devoted exclusively to preliminary track survey and event locating for each instrument engaged in critical analysis of the significant findings. The solution is a stand-attachable scanning-stage design stressing a small assortment of similar components which can be machined in quantity and easily assembled.

General performance requirements for stand-attachable scanning stages were discussed in Section III-A, pp. 37-43. General qualifications for base-mounted stages cannot very well be listed. These will depend on the over-all dimensions and specific purpose of the custom microscope. (Stages used on the custom prototypes listed in Section V-B give some indication of the wide diversity of base-mounted stage types.)

The remainder of this discussion, then, will be concerned with specific component layout and fabrication problems, common in most instances to both classes of stages. Since terminology in this field is not yet formalized, an ambiguous term, or one used in a special sense, will be defined at its first appearance, and will retain that definition thereafter. The several sketches, it is hoped, will also be helpful.

2. Designing Around the Substage Condenser

Way systems for ruling engines, toolmakers' microscopes, precision lathe compounds, etc., often achieve coordinate stabilities and measuring accuracies within tolerance limits for general emulsion work. The custom builder may do well to duplicate structural details of individual way units; however, the main features which assure high performance for such

devices can rarely be incorporated in stages for transmitted-light microscopes. These features are: the direct superimposing of way assemblies over a common center of gravity, the placing of the workload vertically over a way's centerline of travel, and the positioning of lead screws of other driving mechanisms coaxially with the center of mass of the driven component.

In the emulsion microscope the condenser, its bulky mounting and adjusting fixtures, and the substage mirror assembly occupy precisely the region where stage components should be located for maximum stability. Thus, way assemblies must be offset to clear this region, or else designed with two parallel runners or way guides straddling the substage optics. Additional clearance must be considered for the light path between illuminator and substage mirror, and for access of an operator's hand (preferably both hands) to substage aligning controls. Centrally located lead screws must stop short of the condenser area. A stage table or superplate supporting the emulsion will require a rectangular cutout of dimensions equalling the coordinate travels plus the full diameter of that portion of the condenser projecting into it. (One type of superplate is well-illustrated in Fig. 22.)

Offset problems increase with extended travels. Since the upper way assembly normally rides with the moving component or way slide of the lower way assembly, it must either have an offset or a straddling span equaling the full travel of the lower way system plus additional spacing to clear whatever substage component projects from the optical axis at that particular level. For example, a single-unit X way assembly (comprising a fixed way guide, a mating-way slide and a coaxially mounted lead screw) is to be attached to the way slide of a similar Y assembly capable of 4 in. of travel (see Fig. 14). To clear substage optics, the Y assembly is mounted 2 in. to the left of the optical axis. The X assembly is bolted at right angles to the Y slide so that when this is at its near travel limit, the X assembly remains 2 in. to the rear of the optical axis. Thus, as the Y slide moves to its far position, the X assembly is carried to a point at least 6 in. from the microscope optics. The X slide, assuming also a 4-in. travel, will induce an additional vector of offset as it moves toward either limit of its way guide. It is this X slide which must provide the main or only support for the superplate carrying the emulsion strip. Thus, the work load under the objective lens may be as much as 8 in. horizontally removed from the way component supporting it. The moment arm of such an over-hang will of course greatly accentuate any minute chatter or nonlinearity present as either of X or Y way slide is actuated. Outrigged rider bars and glide buttons are frequently installed to reduce the vertical moment effect of overhanging superplates and way assemblies. (See Fig. 17.)

The use of divided way assemblies greatly increases the over-all static stability, if not always the performance, of extended-travel stages. Parallel way guides are located on either side of the condenser region and the way slide bridges between these. Rectangular windows in each bridging way slide allow the condenser to project through. On a 4-X 4-in. -travel stage of this type the slide of the upper way assembly will require at least a 5-1/2-X 5-1/2-in. window; its pair of way guides must be placed some 7 in. apart. Over-all dimensions of such a stage would necessitate a base-mounted design. Additional problems are presented by divided way assemblies: Lead screws should be located midway between the parallel guides to minimize "crawfishing" or binding of the way slide. Thus the screw will have one

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Fig. 14. Offset stage design using two single-unit dovetail way assemblies. Note: With the Y slide fully extended (as shown) the X slide (which carries the emulsion plate) will move along PQ; with the Y slide retracted the X slide moves along line RS. Thus, the center of gravity of support for an event under consideration at E will vary through the extremes shown.

"blind" end--where it is stopped short by the substage optics. On a divided Y way the lead screw will project from the condenser area toward the operator. Here it must also stop short, so that a control knob can be affixed and actuated without conflicting with the operator's midriff. Y travel must often be severely restricted; direct-mounting of motor drives or digital encoders is impracticable. Again, where two divided assemblies are superimposed (this is always done at right angles) the substage area is effectively boxed in on all four sides by the two sets of way guides. Remote-control devices may be required for as many as six or seven hidden focusing and aligning adjustments.

Special stage layouts have resulted from intensive commercial and custom design efforts to minimize conflict with substage optics. Several will be briefly discussed:

a. Commercial designs reduce offset problems of the upper way assembly by providing an extreme minimum of travel for the lower (usually the Y-axis) unit. Two-in. Y travels are maximum, even on such designs as the Koristka R-4, which has an over-all X travel of nearly 6 in. Maximum stability is obtained in certain scattering microscopes either by providing blocking facilities for the Y travel, or by eliminating entirely the Y stage coordinate.

b. A single coordinate X stage is sometimes combined with an entirely separate Y way system built into the microscope arm. The emulsion moves only with the X stage; the microscope arm and the entire optical assembly (including the light source) move back and forth across the emulsion plate in the Y coordinate. Operator convenience obviously requires that the Y travel be relatively short. The Brower scattering microscopes and the 28-in. -throat microscope described on p. 56 are of this type.

c. On stand-attachable stages, especially, substage interference is effectively reduced by mounting one or both of the way assemblies well above the bulkier substage components. Conventional laboratory microscope stages use this expedient with all way units compressed into a 1/2- to 3/4-in. -thick wafer design. Thus, a spanning lower way slide requires a rectangular window only as wide as the tapering cone of the condenser top, and the slide-clip arms of the upper way assembly ride above maximum condenser height. The L. R. L. compact stage Model I, described on p. 42, combines a single-unit Y way assembly offset in the substage region with a comparatively massive single-unit X assembly riding above the stage table. Such designs achieve minimum way offsets and minimum substage restrictions only at the expense of considerable superstage clutter and emulsion-size restrictions. To alleviate this, actual bridging of one or both ways well above the emulsion plate has been attempted. The new Leitz scattering stage suspends its Y travel facilities from such a supporting bridge.

d. Sound engineering would indicate placing both way assemblies beneath the substage area, where they could be superimposed directly over each other and directly under the optical-axis work load. This design is incorporated in the most accurate extended-travel microscope stage to date -- the Brookhaven-University of Chicago instrument described on p. 55.

Structural requirements are relatively simple. (See Fig. 15.) Two massive single-unit way assemblies are directly superimposed at right angles. The way slide of the upper unit is provided with a broad horizontal plate. Stand-offs, or spacer columns, run vertically between the corners of this plate and the actual superplate of the stage. The substage optics project by means of a horizontal branch from the main microscope arm into the space provided by the stand-offs. To accommodate standard substage optics, this spacing between the upper way slide and the superplate must be approximately 5 to 6 in. Unfortunately, adding this span to the combined height of two comparatively massive way assemblies places the emulsion-plate level (and consequently the eyepiece height) of the microscope beyond the torso limits of a comfortably seated operator. However, builders interested in maximum stability and in coordinate travels well beyond feasible limits for designs built around the substage optics, may do well to consider this approach. It is quite possible that broad, low-profile way units and special substage optics can be utilized to decrease the over-all height of such an instrument. (One solution might be a combined illuminator-condenser system such as the Zeiss pancratic condenser described on p. 21.)

3. Fixed and Sliding-Way Members

The performance of an individual way assembly is determined by how well the mating surfaces between its fixed and moving components restrict all movement of the way slide except that of precise linear travel along the coordinate axis. (The way guide itself, will of course have some departure from absolute linearity; however, unless considerable warpage has been introduced by molecular growth of the metal, or by improper bolting down, the radius of curvature of a piece finished on good milling or grinding equipment will be well over 100 ft, and can thus be disregarded.) Single-unit way assemblies must be provided with special dovetail or other interlocking surfaces to overcome vertical lifting from offset work loads, as well as to minimize deflections resulting from localized way and lead-screw irregularities. Divided way assemblies, on the other hand, frequently have way slides of sufficient mass and a work load well enough centered that mating surface contacts need only restrict noise deflections in the horizontal plane.

Various mating designs for divided way components will first be briefly discussed; the complex problems of the single-unit type will then be dealt with.

a. Mating Components for Divided Way Assemblies

Short-travel divided way assemblies are often best fitted with ball-bearing raceways at each contacting surface of the bridging slide.

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Fig. 15. An experimental microscope developed at Brookhaven National Laboratory. The stage employs directly superimposed dovetail ways, placed below, rather than around, the substage optics. This feature was later incorporated in the precision Brookhaven-Chicago microscope described on p. 55.

The extreme minimum of friction supplied by rows of point-contact balls helps prevent binding or crawfishing where there is a wide separation between way guides, or where an offset driving mechanism must be employed. * The custom builder, however, should approach a more general use of ball-bearing way assemblies with caution. It is true that high-performance fine-focus units employ ball-bearing raceways; however, their maximum travel is under 3/16 in. The Cooke two-coordinate ball-bearing stage has been successfully used for scattering measurements into the lower Bev range; its travels are only 1x1 in. The task of obtaining (and retaining) a glass-smooth finish on raceways, and of assembling and holding these raceways in precise parallel alignment becomes extremely difficult for travels of much over 2 in. An associated problem is that of obtaining precisely spherical bearing balls with matched diameters. A careful inspection of the best commercial ball-bearing stages will frequently show that in a raceway fitted with perhaps 10 balls, two or three of these will alone be carrying the load; the others, slightly undersized or oval-shaped, are merely going along for the ride. Friction is of course at a minimum with such few contact points. However, the slightest imperfections in the raceway or in the surface of the supporting balls will produce a chatter in the field of view at normal magnifications. Stage instabilities are highly augmented where two oversized balls happen to lie adjacent to each other rather than well separated along the way-slide raceway. Ball-bearing raceways, then, have limited application to extended-travel stages, and will not be discussed in further detail.

Divided way assemblies with metal-to-metal contact surfaces are much used on base-mounted stage designs. Travels to 10 in. and linear stabilities adequate for multiple scattering measurements have been achieved through use of fixed and sliding combinations such as the following:

(1) Two rectangular cross-section bars of hardened tool steel serve as the way guides. They are suitably base-mounted on either side of the substage optics. A final finish grind is usually taken after assembly to assure that their upper surfaces lie precisely in the same horizontal plane. The bridging way slide is made intentionally massive so that its weight alone suffices to overcome incipient vertical deflections. It should be dimensioned so that its length along the guides is at least twice as great as its spanning width. Brass or cast iron is most often used, with the under surfaces which are to contact the way guides hand-scraped or lightly grooved to help retain a microfilm of oil. Restriction of horizontal motion other than along the line of travel is accomplished by extensions on the under face of the slide; these are spaced to ride against the inner vertical faces of each of the way guides.

* Fitting a divided Y way assembly with a centrally located leadscrew incurs the following complications: If the stage is to be attached to a conventional microscope stand the actuating knob of the lead screw directly conflicts with the microscope arm; when base-mounted with a reversed-arm design, the knob is still awkwardly positioned at the operator's stomach.

While broad oil-film contact areas are essential on the supporting way surfaces, slide retainers contacting the way sides are best designed to provide only small-area contacts for each end of the slide. These retainer extensions are frequently four short blocks machined from a firm, nonmetallic material such as linen composition bakelite to minimize friction induced by heavy spring-loading tensions. Two of the retainers (those contacting the same way guide) are provided with spring-pressure devices to compensate for any variations in spacing between the way guides. Were four fixed retainer blocks to be used, variations in spacing of less than 0.0001 in. would have to be maintained. This is not feasible for long ways such as the 10- to 12-in. pairs normally used for 4 in. of slide travel.

Way assemblies of this type attain maximum performance when carefully lapped-in. A mechanical reciprocating device can be set up to automatically actuate the way slide through full travel several times a minute. The process is often carried on for several days. Where an 8 microinch or better finish has already been achieved in the finish grind of hardened steel ways, a copious use of light machine oil is preferable to even the finest grit-lapping compounds. Installing and lapping-in lead-screw drives for stages of this type are discussed on pp. 93-99.

(2) A variation of the above way configuration utilizes precision-ground cylindrical way guides. Only one cylindrical way guide is actually necessary; the other may be a rectangular bar similar to those described above. This design calls for two V-shaped blocks spaced to ride well apart along the cylindrical way and attached to the under surface of the way slide. Each V is machined to contact the cylindrical surface at two points with an included angle of about 120 deg. Thus, a total of four points (or rather four short lines of contact) serve to restrict the way slide from horizontal digressions and to support half the load on the slide. The remainder of the vertical load is relegated to a glide button, or small-area contact surface, positioned across the span of the slide and riding on the rectangular way guide. Through this method, friction is considerably reduced, the need for spring-loaded retain blocks is eliminated, and spacing between the two guides is not critical. However, unless the way slide and any superstructure it carries are of considerable combined weight, the driving torque (as well as any eccentricities, or runout) of a lead screw can introduce marked instabilities.

(3) A way guide of standard dovetail configuration can be made to straddle the substage region. It is best machined as one piece, with a very broad separation between dovetail surfaces to permit an integral substage window cutout. The way slide is provided with mating dovetail surfaces and spans the substage region with an appropriate rectangular cutout. The dovetail retainers effectively counteract vertical noise; thus a heavy vertical load on the slide is not essential, and the unit may find applications on stand-attachable stages of modest travel.

Frequently, this design is used as a short Y unit to support X way assemblies such as discussed under (1) and (2) above. For such applications very broad dovetail and horizontal mating surfaces are indicated. Friction from such massive loads is excessive unless proportionately large-area oil-film support is provided.

Adjustable gibs, lead-screw mountings, and general fabrication for this design will be essentially the same as for the single-unit assemblies next discussed.

b. Mating Components for Single-Unit Way Assemblies

Dovetail ways can be designed as a compact unit when used in offset stage assemblies such as described on p. 42. Extended travels require only a modest dimensional increase of this basic unit. Provisions may be made for an integral lead-screw drive: The lead screw is supported by a bearing block attached to one end of the way guide; it actuates the slide by means of a threaded insert or drive nut and projects on through a clearance hole in the slide as travel demands.

Careful attention to component structure can add versatility to ways of this type: they can be designed for preassembly and lapping-in as self-contained units; efficient fabrication in quantity lots will be possible - especially where the X and Y units incorporate identical dovetail configurations and are dimensioned to take similar slides, bearing blocks, gib strips, dial knobs, drive nuts, etc.; an ample number of symmetrically arranged mounting holes (especially in hardened way guides) will permit several distinct stage types to be assembled from "stock on hand." The designer may keep such features in mind along with the following more basic considerations:

The Way Guide: This must have a sufficiently massive cross section so that when attached near one end only to a supporting base (or to the slide of a second way unit) it can still adequately handle weight and torsional stresses incurred as its slide moves through full travel. If it is to be self-contained, the way guide must not depend on any stiffening or strengthening effect derived from its being bolted to a supporting surface.

The anticipated load must be considered in working out the oil-film contact area required to prevent frictional sluggishness of a mating slide. (The available contact area will be determined by the width of the horizontal and the 60-deg dovetail surfaces, and by the length of a mating way slide.) The moment which will be induced by an anticipated load at maximum offset position should determine the width of the dovetail tongue and the total width of the way guide. Figure 16 shows typical way-guide cross sections for self-contained way assemblies used on L. R. L. stand-attachable stages.

The material used in fabricating a way guide will also affect the cross-sectional area and thus the weight and general bulkiness of the assembly. Both space and weight are critical limitations on stand-attachable designs; here, maximum strength for a given cross section is best achieved with a way guide of high-tensile-strength tool steel.

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Fig. 16. Typical way-guide cross sections for self-contained way assemblies used on L.R.L. stand-attachable stages:

- (a) End view of a Y way guide normally 11-in. long and used with a 6-1/4-in. way slide to carry approximately 12 pounds of X-way-assembly and superstage load through 12 cm of travel. Maximum rigidity permits the guide to project unsupported after being bolted to a base plate for a short distance along one surface "A"
- (b) End view of an X way guide of up to 12-in. length and designed to carry a maximum of 2 pounds of combined plate-holder and emulsion load through travels to 22 cm.

Note: Special jigs are used to center the dovetail precisely with respect to surfaces "A." Surfaces "B" are ground to be flat and in the same plane within 0.001-in. in 12-in.

It should be machined, hardened, carefully stress-relieved, and finish-ground. Fine-grain graphitic steels* will take a 4-microinch finish grind. Such surfaces mate well with light-weight aluminum alloy slides. Where total weight and bulk of the assembly are not critical (as in certain base-mounted applications) the use of a well seasoned cast iron, such as meehanite, for both guide and slide has proved highly effective.

Machining problems of one-piece dovetail way guides may be a stumbling block. Often, alternatives such as fabricating separate dovetail strips and bolting them to a flat way bar are resorted to. This recourse normally adds more to assembly and lapping-in time than it takes from complex machine setups. One-piece dovetails are no longer a problem at the Berkeley machine shops of the Lawrence Radiation Laboratory. Special gages have been devised to overcome the difficulties of taking precise reference measurements from the sloping dovetail faces. Special jigs are used to hold the semifinished guide at the most convenient angle for a standard horizontal-shaft surface grinder and standard grinding wheels. Moreover, such a jig permits turning the piece end-for-end to duplicate exactly the location and the angle of the opposite dovetail surface. Thus, the difficult problem of centering the dovetail on the width of the way is fully overcome. (Centering of the dovetail is essential if bearing blocks, drive nuts, and lead screws are to be interchangeable; it eliminates the tedious process of mating each way slide to a specific way guide and then clamping these together and line-boring the bearing block and the way slide to assure concentricity of the lead-screw mounting with a drive-nut insert. Also, a symmetrical way guide may be mounted on either of its narrow sides for diversified applications.)

The Way Slide: A stage utilizing two single-unit way assemblies will have at least 75% of its weight set into motion whenever lead-screw torque is applied to the slide of the lower way unit. This is usually the Y way slide. The several pounds of load it moves will have a center of gravity far to one side of its drive-nut contact with the lead screw. Inertial resistance is then essentially at right angles to the axis of the Y travel and tend to force one end or the other of the slide away from contact with its guide whenever Y travel is suddenly initiated or changed in direction.

* An air-hardening graphitic tool steel, Timken "Graph-Air," is used almost exclusively for stage way guides at the Lawrence Radiation Laboratory. Growth-induced warpage on 10- to 14-in. ways is negligible in most cases. Similar ways of case-hardened mild steel, as well as of certain oil-hardening tool steels, have shown continuing growth from molecular instabilities over periods of three to five years. Warpage sometimes increased as much as 0.008 in. along 10-in. surfaces.

The resulting instabilities can be nullified in the vertical plane by providing a glide button and auxiliary rider-bar bearing surface. (This unit is normally located at the overhang extremity of the X way guide, as shown in Fig. 17.)

Displacement in the horizontal, or emulsion plane will still be present (or even augmented by friction from the glide button). It is observable in the field of view as an X-axis shift, or coupling, occurring just as the Y travel is set in motion. Coupling can prevent effective use of the Y coordinate for measuring purposes. Also, it is disconcerting to the microscopist, even when he is engaged in preliminary scanning routines. However, an exceptionally long Y slide, provided with strong gib-clamping facilities very near each end, can greatly reduce coupling. For example, the Y slide of the L. R. L. large-plate scanning and measuring stage is 6-1/4 in. long; one of its internal dovetail surfaces is fitted with a gib strip (Fig. 18) which is held tightly against the dovetail of the mating way guide by two pairs of spring-loaded push rods; each pair is located within an inch of either end of the slide. Coupling from the inertial drag of some 12 pounds of offset load is held within 1 micron of observable X-axis shift.

Offset loading on the X way slide will be comparatively light. A shorter slide with similar gib-strip pressure points is usually adequate to overcome any coupling tendencies here.

The bulk of both X and Y slides will still be considerable owing to the thick cross section required for the dovetail slot, for mounting the drive nut, and for a clearance hole to accommodate a large-diameter lead screw. Weight is best reduced through use of aluminum alloy. Stress-relieved 2024-T dural provides maximum structural rigidity as well as wear-resistant sliding surfaces. Its free machining property aids milling of the internal dovetail. Gib strips are usually made of a spring material considerably softer than the way-guide steel. Beryllium copper, which can be retempered, is best used where a retainer pin (such as shown in Fig. 18) is to be soldered directly to the gib.

A way guide and slide are carefully lapped together, with gib strip installed and under considerable spring tension. (The procedure is essentially the same as that for divided way units discussed on p. 79.) It is important to determine whether or not maximum contact with the way guide is being made at both ends of the slide. A minute bow of the way guide, or a slightly convex surface on the slide will induce a rocking instability and greatly accentuate the coupling effect discussed above.

* A close-fitting retainer pin or comparable gib retaining device is essential. Stage noise and torque variations may often be traced to the momentary lag (end play) of a gib strip as its slide is moved through short positioning travels.

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Fig. 17. Offset stage assembly, showing glide button and rider bar for additional vertical support of overhang.

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Fig. 18. Gib strip and typical installation on way slide of single-unit way assembly.

4. Parallel-Blade Distortion Stages

There is at least one known means of providing linear stage travel without the use of fixed- and sliding-way members. This is the parallel spring-blade suspension system illustrated in Fig. 19. The basic principle is that two thin strips of spring material can be joined in a U-shaped configuration to constrict the curve and lift tendency of each to a purely linear motion. If the strips are made wide enough, there is high resistance to any motion at right angles to the "linear distortion." This feature prompted M. G. E. Cosyne to apply the parallel-blade principle to scattering-stage design in 1951.¹⁵ It has been utilized on several experimental stages, and with signal success on the Koristka MS-2 -- not only for the main scattering stage, but for maximum linear stability of the Z movement as well.

A full two-coordinate stage of this type seems impracticable; however, an X travel of parallel-blade type may be carried by a Y unit of conventional divided-way design. Advantages of the parallel-blade-distortion design are: (1) maximum rigidity against deflections or noise at right angles to the line of travel; (2) the open center configuration is especially adaptable to mounting around substage optics; and (3) the complex machining and fitting, as well as the friction and wear problems of sliding way components, are eliminated.

The following major limitations must also be considered:

- (1) Maximum travel of perhaps 2-1/2 in. (the vertical length of the blades is perhaps best kept at least twice that of the translation; over-all microscope height becomes inconvenient when blade lengths exceed 5 in.).
- (2) Although fabrication is comparatively straightforward, the proper blade material presents a major stumbling block. A total of eight blades (two pairs at either end of the moving component) is normally required. These must all be closely matched in thickness and in tensile strength and must be essentially free of individual surface or internal flaws.
- (3) The lead-screw drive, discussed in the next section (p. 95) is extremely critical.
- (4) It might be mentioned that an event under observation on the emulsion table moves through a slightly curved trajectory in the vertical plane. With adequate blade length, height differences may perhaps be held within 1 micron per mm of travel.

The extremely low Y noise of the Koristka MS-2 stage would seem to indicate the superiority of parallel-blade-distortion systems and the advisability of incorporating them in custom designs. Experimental parallel-blade stages have been under development at research centers in Sweden, Canada, and elsewhere. Any signal successes have yet to be reported. Undoubtedly, many of the design problems worked out by Dr. Cantu and his associates for the Koristka stage are more complex than anticipated by custom designers.* Indeed, certain MS-2 features are held under patent.

*An extensive theoretical and functional analysis of the parallel-blade-distortion stage has been conducted by J. E. Plainvaux.¹⁶

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Fig. 19. Single-coordinate parallel-blade-distortion stage, showing hypothetical system for double lead-screw drive.

It may be well to consider the following alternatives to custom-designing a parallel-blade-distortion stage: (1) A divided way assembly such as described under item (1) p. 78, can be built with comparable Y noise tolerances, and with the assurance of less vertical curvature. (2) The purchase of a Koristka M rather than attempting a similar stage. The major inadequacy of the MS-2 for large-plate scattering is its throat depth. This is not difficult to modify. At the Lawrence Radiation Laboratory the throat capacity of a MS-2 model was recently increased to 10 in. (See Fig. 25, p. 123.)

5. The Lead Screw

A fine-pitch lead screw is at present the best means for obtaining slow, nicely controlled stage translations. Until recently it has provided the only means for measuring extensive stage travel in small units.* However, since no perfect lead screw has ever been machined, and since it is rarely possible to transform rotational torque into a purely linear push, lead-screw drives can be expected to contribute additional noise and dynamic instability to any type of way system. The magnitude of the lead screw's imperfections, and the manner in which these are transferred to the moving stage component (through a drive nut or related contact device) determine the ultimate precision of the stage.

A 1-mm-pitch lead (10 threads per cm) is normally used.† The resulting travel is slow enough for accurate corsshair positioning of events, and is most convenient for standard 100-division dial and 1-mm linear scale engravings. A more rapid traverse is sometimes desirable where scanning procedures involve extensive plate-positioning maneuvers. This is usually taken care of by a crank handle on the dial knob; cranking eccentricities, however, can dangerously strain light-weight stage components.

The major diameter of the screw warrants careful consideration. A maximum diameter compatible with over-all weight and dimensional limitations of the stage should be used. Axial eccentricities, or runout, due to the flexing of the screw during macining or grinding are directly related to diameter-per-total-length of the lead-screw shaft. A larger diameter also means more surface-area contact per thread, giving less wear on a short-drive nut and in most cases lower frictional torque due to increased oil-film contact areas. Lead screws of 20-mm (or even 1-in.) major

* Direct small-increment readouts are possible on the new Leitz scattering stage discussed on p. 51. Linear digitizing systems are now available (see Section VI).

† International 60-deg metric thread form is standard. The possibility of using a square thread has yet to be investigated. Such a thread would in most cases nullify the effects of pitch diameter variations and of lead-screw eccentricities or runout. The writer has been assured by at least one thread-grinding concern that threads as fine as 1-mm pitch are feasible, using either an Acme or a true square thread form.

diameter are common on base-mounted divided way assemblies. Such diameters are of course out of the question for stand-attachable stages. On the other hand, the frequently used 8-mm diameter screws (for which standard metric taps are available) will be found too light for most extended-travel applications. A 12-mm screw is now used on all L.R.L. stand-attachable stages in an effort to minimize flexing and warping during fabrication. The thread-area diameter cannot of course, be retained for the full length of the lead-screw shaft. Bearing journals or lands normally undercut the root diameter of the thread (often by a considerable amount to accommodate special bearings). Threads for bearing retainer nuts and a final extension for the dial handle reduce shaft diameter still further. Since the entire shaft length must be placed between centers for machining, small-diameter extensions at either end of the thread area should be kept as short as possible. A typical lead screw for L.R.L. stand-attachable stages is shown in Fig. 20. This screw is designed with a bearing land at one end only (surface B). The land is of precise diameter to accept a "duplex" set of ball bearings giving combined radial and thrust control. Dimensions for root diameter, pitch diameter, and major diameter are taken from International metric thread form tables for the standard 8-mm-diameter 1-mm-pitch screw size; each dimension has been increased by 4 mm to give the 12-mm O.D. desired. Pitch-diameter variations along the run of the screw must of course be kept very minute if the drive nut is to fit equally well during its full run. Lead error is not as critical as for stages employed in absolute measurements, owing to the fixing and mounting distortions present in nuclear emulsion plates. Accuracies between 0.5 and 0.1% are normally sufficient for measuring an accomplished transport of the emulsion. However, since a certain percentage of the lead-screw advance will always be deformed or transferred to other than purely linear stage advance [see p. 107, item (c)] a maximum error in thread lead well under 0.1% is certainly advisable.

Sometimes it is necessary to add a small-diameter extension to the free end of a screw (such as the one illustrated in Fig. 20) to accommodate motor drives or digital encoders which conflict when connected with the dial knob extension. In this event, special precautions must be taken to overcome induced stresses or off-axis torque from the coupled device (see p. 120).

Long screws of much over 1/2-in. diameter will normally require bearing journals at either end of the shaft. The general design and dimensioning of lead-screw journals will be directly influenced by anticipated lapping procedures (p.93).

Fabrication of the lead screw calls for a primary decision as to whether the threads are to be lathe-cut or hardened and ground. (Hardening necessitates grinding, although grinding is sometimes used for threading unhardened screws as well.) The writer hesitates to take sides on this still unresolved controversy. It is evident that neither lathe-cut nor ground screws have yet been made accurate enough for many emulsion-stage applications. Extensive lapping, compensating drive nuts, etc. are still essential. However, some generally conceded advantages and disadvantages of each method will be listed:

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Fig. 20. A typical lead screw for L.R.L. stand-attachable stages. Specifications are as follows:

1. On Surface "A" Grind 1 mm Pitch 60° International Metric Threads:

Pitch Dia.: 0.4470 with .0004 max. variation any single screw.
0.4460

Minor Dia.: 0.4180 with .0004 max. variation any single screw.
0.4170

Lead Error: Maximum error for any one cm to be 0.00008 in.
or 0.002 mm.

2. The Following Concentricity Tolerances with Respect to the Axis Through the Centers Must be Held:

A. Thread Major Dia.: .0006 T.I.R.

B. Thread Root Dia.: .0003 T.I.R.

C. Surface "B" Dia.: .0002 T.I.R.

Lathe-Cut Lead Screws: a. Here the lead-screw blank cannot be of much more than 30 Rockwell hardness for working with a lathe tool. Hardening after thread cutting is out of the question. These softer screws are more prone to wear and especially to scoring from abrasives such as glass particles chipped from constantly maneuvered emulsion plates. Smaller-diameter unhardened screws tend to stay bent after an inadvertent bumping of the way assembly, or from the strain of a rapidly cranked way slide colliding with a travel limit stop.

b. Lathes standard in most U. S. machine shops are rarely designed for cutting metric threads. Conversion gearing introduces inaccuracies as well as problems of thread pickup for each cutting pass. The duplicating of close-tolerance dimensions where a quantity of lead screws are to take interchangeable drive nuts and precision bearings is an extremely taxing and time-consuming lathe operation.

c. On the other hand, it can be shown that lathe-cutting of threads produces less axial and longitudinal screw distortions than does grinding.* Either there is less tendency to disturb stresses inherent in the blank, or fewer stresses are induced during the cutting of the helix. High-stability nonhardening steels, often used for lathe-cut screws,† will respond very erratically when the helix is ground. Most pronounced is a sort of "unwinding" warpage reaching maximum amplitude near the thread end where each grinding pass is completed. On identical 12-mm-diameter blanks the resulting major diameter runout at this point may be 5 to 10 times as great as for lathe-cut threads. (A large major-diameter shift accompanied by very little thread root eccentricity with respect to the shaft axis indicates that the stresses inherent in the blank were all released during the first few passes of the wheel. Considerable runout of both major and root diameters indicates additional stresses being released or new stresses induced throughout the entire threading procedure.)

d. Thread form and pitch diameter required for a matched lead-screw and drive-nut set are most precisely determined through repeated trial fittings of external and internal threads while they are in fabrication on the same lathe setup.

* Here one must distinguish between axial warpage due to metallurgical stresses and a simple bowing or flexing of the blank due to excessive end thrust of the holding centers of excessive pressure from a cutting tool or wheel caused by attempting to remove too much material per pass. Again, thread drunkenness (localized lead-and-lag distortions) can be attributed to longitudinal twistings and expansion of the metal, or even more likely to excessive vibration, looseness of ways, spindles, etc. of the fabricating machinery.

† Specific examples are the La Salle "stress-proof" and "fatigue-proof" alloys. Stress-proof, especially, is often used for large-diameter turned screws on precision measuring stages.

Hardened and Ground Lead Screws: a. Research centers rarely have available the specialized thread-grinding and heat-treating equipment for producing hardened lead screws. The task is usually turned over to commercial thread-grinding specialists. Some problems connected with this procedure might be listed:

1. Few qualified concerns are willing to undertake close-tolerance grinding on small job lots. Among these, few can guarantee metric threads of better than nominal lead accuracy. Since over-all lead error is not exceedingly critical for most emulsion applications (as explained on p. 89) blueprint specifications should treat this leniently. More critical is lead error within one turn of the screw, or thread drunkenness due to loose grinder ways or an identical drunkenness in the master screw.* (Thread drunkenness induces a snaking advance to the stage way slide; this, on an offset-way system can engender larger readout errors than major discrepancies along the run of the screw.) Again, lead variations which are alternately shy or excessive over a centimeter or so of thread run are troublesome, but more from the point of the drive nut fitting against alternate bind and slop than from endangering emulsion measuring tolerances.

2. The best-qualified grinding concern may rightly hesitate where an unfamiliar steel is specified; it is sometimes best to designate only the hardness and surface finish desired, with choice of material and accompanying metallurgical problems left up to the manufacturer.

3. No quarter should be given, however, in stating requirements for concentricity of thread and bearing-land surfaces. It is almost impossible to lap the warp from a bowed or skewed pitch-diameter axis. A close-fitting drive nut will describe a circle during each screw revolution which is equal in amplitude to the runout of the pitch diameter with reference to the axis through the bearing lands.† The manufacturer can best be alerted (and at the same time the customer best protected) through clearly stated runout tolerances such as given for the lead screw of Fig. 20, p. 90. Here, the most important total indicated runout -- that of the pitch diameter -- is not mentioned. However, runout of this difficult-to-measure position will be essentially the same as for the thread root diameter which can be sharply focused on a comparator screen, or microscope measuring reticle. The runout of the major diameter of the thread is less critical, since it has little to do with the wobble of the drive nut as long as the pitch diameter remains true, and as long

* Some thread-grinding equipment may present the same change-gear problems as standard American lathes. More widely used, at present, are grinders designed to take interchangeable master driving screws. A 1-mm-pitch thread requires a 1-mm-pitch master. Any thread inconsistencies in this (which may or may not have been made to precision tolerances) are faithfully duplicated in the customer's screw.

† For measuring convenience it is often expedient to refer all concentricity tolerances to the axis through the shaft centers. However, the "unwinding" warpage is often so erratic as to cause bearing-land runout to be quite diametrically opposed to runout of the pitch diameter (or as measured, the root diameter). Thus, maximum wobble imparted to a drive nut from the bearing-mounted lead screw may be the compounded runouts of both bearing-land and pitch diameter.

as the extended thread apex on the high side does not dig into the root diameter of the drive nut.

b. The fitting of ground lead screws with drive nuts is sometimes a problem. Lathe-cut internal threads may require considerable lapping to mate well. Taps of 1-mm pitch are standard only to 8- or possibly 10-mm diameter. Perhaps the best solution is to have taps ground concurrently with the lead screws and on the same machine. Dimensions should be carefully worked out to conform with pitch-diameter tolerances for the screws. Often, lead screws with near-perfect pitch-diameter concentricity, but with considerable major-diameter runout are encountered. These can sometimes be salvaged if the drive-nut tap is designed for a maximum major diameter obtainable (within the limits of structural stability as a point apex of thread is approached) for the given pitch diameter.

c. A 60 to 63 Rockwell harness and precisely plane V surfaces of 4-micron-inch (and better) finish are highly desirable qualities for many lead screw applications. Semi-automatic grinding machines are available for rapid duplication of 1/10,000 inch dimensional tolerances on any quantity of identical screws. The remaining drawback to wide application of ground leadscrews to microscope stages is basically metallurgical -- the adverse and erratic reaction of present steel alloys, hardened or unhardened, to the grinding of the helix.†

6. Lapping and Installing the Lead Screws

Certain lead-screw imperfections can be greatly reduced through skilled lapping prior to installation. Among these are roughness of lathe-cut threads, variations in pitch diameter, thread drunkenness, and variations in lead. Bowed or skewed pitch diameters, typical of ground screws, are the most difficult to straighten through lapping. Here, little success can be expected with long, smaller diameter screws, owing to their flexibility.

* A considerable eccentricity of the thread apex will normally be accompanied by bearing-land runout, even where the journals are close to the shaft ends. As explained in item (c), p. 91, it is quite possible in such cases for the pitch diameter to remain true to the shaft axis. Lead screws with true-running-pitch diameters are well worth salvaging. The shaft may be held by its centers and a careful cleanup pass taken with a flat-faced grinding wheel on both thread apex and bearing land to true these with the pitch (or root) diameter. (There is, of course, the possibility of inducing or releasing additional stresses.)

† A recent lead-screw order placed with a commercial grinding concern showed an unusually high percentage of screws well within specified tolerances. A combined technique appeared to have solved the warpage problem: threads were lathe-cut to a close clean-up tolerance and then the workpiece hardened to 60 Rockwell and finish-ground. Among the best were several 12-mm-diameter screws with a full 10 in. of thread run. Unfortunately, a subsequent order fabricated in identical manner failed to confirm the advantages of this method. Of 18 screws with 8 in. of thread run, more than half fell far outside concentricities realized on the longer screws of the preceding order.

Extensive lapping (as opposed to the light thread-polishing and drive-nut lapping required on all screws) is best carried out on screws of comparatively large diameter-to-length ratio. Contours of the screw must be designed to permit considerable overriding at both ends of the threaded region for a long lapping nut. (For example, the screw shown in Fig. 20, p. 90, is not so designed, owing to a projecting contour adjacent to one thread end.) Since extensive lapping will almost certainly achieve a new axis of pitch diameter which is no longer concentric with that of the bearing lands, some means must then be devised to hold and rotate the screw precisely about its pitch diameter while the bearing lands are themselves lapped concentric to this axis.*

Lapping procedures vary widely; one method will be briefly described: a special lapping nut, at least one third the length of the thread run is fabricated,[†] split lengthwise into two or more segments, and provided with spring-pressure take-up adjustments. The screw is supported vertically and the lapping nut permitted to essentially float free, except for wing extensions running loosely in guides to prevent its rotation with the screw. A heavy lapping nut must be counterbalanced to overcome unequal lapping pressure on one thread side. Either the nut or the screw must be of a comparatively soft material so that the lapping compound can embed itself in one surface more readily than the other. Grits of varying fineness are used, but all must have the property of "breaking down" to permit thorough flushing of residual compound from the assembly. Lapping is best carried out intermittently, several hours a day, over a period of several weeks. Lapping nuts are changed end for end and their component sections rearranged in all possible combinations; frequently several lapping nuts will have been worn out before the screw reaches a desired maximum straightness. The success of extensive lapping depends on how careful a check is maintained on the progressive improvement of the screw. Tendencies toward local "over-lapping" must be immediately

* In this case, the bearing-land diameter will of course be undersize for any predetermined fit. This is one good reason why high-precision screws are still normally mounted in custom-fitted friction-type bearings, even though sufficiently precise commercial ball bearings are now available.

† This is also a difficult problem for smaller-diameter screws. A long small-diameter lapping nut may be extremely difficult to thread with a lathe tool or even with a tap of normal reach.

caught and remedied. Ingenious checking devices have been employed, including the mounting of interferometer components on special test nuts to directly determine remaining runout of pitch diameter and thread drunkenness (or the total periodic error). Detailed descriptions of such devices and of lapping procedures which have produced near-perfect lead screws are found in the considerable published literature on ruling-engine construction.*

Mounting the Lead Screw: An excellent but poorly mounted lead screw will severely limit performance of a way system. On the other hand, screws with major defects can often be made to perform efficiently through carefully designed mountings and compensating drive nuts. Two distinct mounting methods are utilized on microscope stages. (a) The micrometer screw drive combines bearing mounting and drive nut in one rigid unit. The screw itself advances as it turns, pushing the way slide. (b) The bearing-mounted lead screw is restricted to a purely rotational movement; a drive nut advances along the helix to actuate the slide.

Micrometer screw drives have the advantage of simplicity, of permitting a point contact with the way slide (which minimizes conversion of screw noise into stage noise), and of rotating around their pitch-diameter axis rather than a possibly eccentric bearing land axis. They are effectively employed on the Cooke stage described on p. 52, and on the Koristka MS-2. The special requirements of the parallel-blade distortion stage, however, make the application far from simple. As sketched in Fig. 19, p. 87, a double micrometer drive is necessary; the screws must be geared so that a constant two-to-one ratio is maintained between them.

Micrometer drives of more than 2 in. travel are rarely utilized on microscope stages. Instabilities of the screw as it projects farther and farther from its drive-nut mounting are greatly augmented by the need to spring-load or weight the moving stage component so that it will always press firmly against the screw end. Thus, the wear on the threads and the driving torque will be more than double that required where a drive nut both pushes and pulls the way slide. [This may be minor on a low-friction ball-bearing stage such as the Cooke, but soon becomes excessive on mating-surface way assemblies, where sufficient spring loading must be applied to overcome inertial starting or "stick-slip" friction, in addition to controlling the shear weight of the unit. Moreover, as the screw is retracted, the actuating knob will project farther and farther from the stage. Aside from inconvenience, excessive instabilities will be induced through even the most careful manipulation by the operator (unless, as on the Koristka, a flexible, shock-mounted control knob can be devised).]

* Diffraction-grating ruling engines are among the most precise lead-screw-driven mechanism in existence. Descriptions of these often include considerable information on lapping of the lead screws. ¹⁷

Bearing-mounted lead screws are necessary for most sliding-contact way systems, and certainly where extended travels are provided. The screw is supported and restricted from end play either by a bearing assembly near one end (as discussed on p. 89) or by bearing mounts at either end. However, even with bearing supports at both ends, screws will function best (unless of very massive shaft diameter) where facilities to restrict end play are built into a bearing unit at one end only. * Thrust-bearing designs which compress the entire shaft length between them will augment bowing and warpage tendencies even when the screw is of considerable diameter. This is especially true of ground screws where residual stresses are always present. †

Precise alignment of the lead screw with the line of travel of the way slide is, of course, essential. This is facilitated by mounting the bearings in adjustable bearing blocks which can be set to exact alignment after assembly of the unit, and readjusted as wear or growth distortion of the way components demands. The bearing blocks are normally centralized on the fixed-guide component so that the screw will transfer thrust through its drive nut to the slide at a point equally spaced between the mating-surface slide and guide contacts. Hence, on a single-unit dovetail assembly (p. 80) the bearing block is located to center the lead screw directly over the dovetail tongue. On a standard divided-way assembly (p. 78) the screw is best positioned midway between the fixed guide bars. More precisely, the screw's drive nut should contact the way slide at the balancing point for the frictional loads at either end of its span. Where the two frictional loads are unequal [as with the cylindrical guide assembly discussed on p. 79] the proper balancing push-point must be determined experimentally. This can be accomplished with a long arm affixed to the way slide and at right angles to the line of travel. §

* Where ball bearing mounts are contemplated, a matched set of preloaded bearings can be used at one end for both support and end-play control, and a single support bearing at the other end. Where solid bearings are to be used, "zero lead threads" and other positive restricting devices are frequently used. Special bearings for end-play elimination are discussed by G. R. Harrison.¹⁸

† Stresses present in ground screws may be affected by seemingly insignificant shaft compressions. Excessive tightening of a retainer nut against the inner races of a duplex ball-bearing set used on the lead screw shown in Fig. 20, p. 90, can induce a 2 to 3 thousandths runout of the thread surfaces. Fortunately, resilience of hardened screws of this type is such that when the retainer nut is slightly backed off, the shaft again resumes its original straightness. This phenomenon seems quite consistent on ground screws of this type. Numerous tests have been made with a simple sleeve about 1/2-in. long replacing the ball bearings. When the retainer nut is tightened against the sleeve to about 2 ft-lb of torque, a bow running the full length of the shaft appears and is readily observed by the naked eye as the lead screw is held and rotated between centers.

§ An interferometer or other small increment-measuring device at the arm end will show maximum and minimum tendencies of the slide to teeter or crawl as various push points across the slide span are tested. Such testing should be carried out with the slide set up in operating condition and supporting the full superstage load it will normally carry.

Drive Nuts These are quite as varied in design as the custom stages they are used on. The most successful attempts toward converting screw rotation into purely linear thrust against a way slide have all resulted in drive-nut assemblies far too bulky for most two-coordinate-stage applications, and far too intricate to be economically fabricated. The least success has been achieved where compensating drive nuts are most needed, i. e., on stand-attachable stages using small-diameter lead screws. Such screws (in the vicinity of 10- to 14-mm diameter) are both the most susceptible to distortion during fabricating and the least suitable for straightening through extensive lapping. Backlash due to drive-nut wear is many times more pronounced, not only because of less total thread contact area, but because stand-attachable stages bear the brunt of full-time scanning operations.

Several drive-nut types will be briefly discussed, with some evaluation of their special features:

a. "Floating" drive nuts find restricted application on large base-mounted measuring stages. A wing projecting from the nut rides on an auxiliary way guide. This prevents both rotation of the nut and the transference of rotational torque to the moving stage component. Another projection makes point contact with a highly polished flat jewel or steel plate centrally located between both the span and the length of the slide. Carry-over of lead-screw eccentricities is almost fully eliminated where the slide can be spring-loaded against a single point contact with the drive nut. However, where the drive nut is to both push and pull the slide, two opposing point contacts must be provided. Although each may press against a highly polished surface, any clamping tension between them which is sufficiently strong to prevent backlash as the stage is reversed will cause some carry-over of lead-screw runout. Long drive nuts are used, with a central region relieved of threads. Such an arrangement spans and considerably offsets the effect of local variations of lead. Lead error can be further reduced by contouring the auxiliary guide to induce slight rotational increments to the drive nut at points along the screw where calibration charts show lead departures.

b. A swinging or flexing drive-nut mount has been effectively employed on several custom scattering-stage designs. A rectangular nut is suspended from the way slide by means of two wide-leaf springs, one bolted along either side of the nut. Each leaf spring is made up of several sheets of 0.005- to 0.010-thick phosphor-bronze sheet. Thus, the drive nut swings from side to side with lead-screw eccentricities, yet retains sufficient rigidity for positive transfer of lead-screw thrust along the line of travel. The Y stage noise that would normally result from screw runout is almost fully eliminated.

c. A "floating-section" drive nut has been developed at the Lawrence Radiation Laboratory to overcome the wear problem of threaded inserts normally used on single-unit way assemblies (Fig. 21). The drive nut is a thin-walled tube with a flange at one end for bolting to the face of the way slide. The tubular portion projects well into the slide. Clearance for the lead screw is provided except for 1/2 in. of nut threads at the unflanged end. A 100-deg sector is cut from the tube along the threaded region. This loose thread-sector is held in place against the lead screw by a pair of spring-loaded push rods contained in the slide-block wall.

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Fig. 21. Floating-section adjustable drive nut developed at L. R. L. for stand-attachable microscope stages.

Set screws provide quick adjustment of spring tension to achieve any desired minimum of backlash.* Thereafter the floating section will automatically compensate for wear until the nut threads are excessively worn away.

In most cases, drive nuts are partially lapped to their lead screw during preliminary fitting. The final lapping and running-in, however, must be done after the way unit is fully assembled with lead screw and drive nut aligned and secured in final operating position.

7. Limit Stops and Visual Readout Facilities

Two additional problems are connected with lead-screw installation: limit stops and visual readout facilities. These will be briefly discussed:

Limit Stops The lever advantage of a fine-pitch screw is considerable. Rapid turning of a control knob on a comparatively light scanning stage can cause a crashing impact when an obstruction is unexpectedly reached. The most cautious operation of a heavy stage unit (where inertial drag and stiffer lead-screw torque tend to muffle the instant of contact) can exert damaging pressures against substage optical mounts or other delicately aligned components. In all such cases, positive stops should be provided to define travel limits.

On stages with heavy moving components, and especially wherever floating or suspended drivenuts are employed, the limit stop is best positioned to stop the lead screw itself, rather than contact the way slide or drive nut. The following method is often used: Linkages are set to be actuated by the way slide at either extreme of its required travel. These in turn depress a pin mounted in the bearing housing or a special backing plate, so that the pin protrudes to contact a detent in the control knob; the knob is thus locked against further turning in the same direction. Hence, the screw is stopped at the point of torque application without in any way straining way guides, drive-nut mountings, or screw threads. An alternative to this mechanism (which is often difficult to synchronize) might be a microswitch stop that is set to activate a warning light or buzzer as travel limits are approached.

* Backlash can never be entirely eliminated in a drive-nut and lead-screw fit. The operator must always "take up backlash" by reapproaching a measuring point from a predetermined direction, if the point has been overshoot. Minimum desirable backlash will normally lie in the vicinity of 10 microns for a 1-mm-pitch screw. This is a small enough increment of rotation (3.6 deg) to require very little take-up manipulation, but enough to remind the operator that a take-up procedure is necessary. (Backlash is only fully overcome on a stage where the moving component is spring-loaded or weighted to press the drive nut against one side of the screw threads at all times. Here excessive torque and wear offset the advantages of no backlash for many applications.)

Visual-Readout Facilities Graduated drum dials are normally fitted along with the control knob at one end of the lead-screw shaft. Direct readout in micron units is frequently provided for base-mounted measuring stages. This entails a dial diameter of approximately 8 in. if the 1000 graduations (assuming a 1-mm-pitch screw) are to be adequately spaced for reading with the unaided eye. An even larger diameter is sometimes used to permit estimations or vernier readings to tenths of a micron. Simple or compound magnifying lenses may be used to achieve similar readouts on smaller-diameter dials, providing the line engravings are extremely accurate and finely delineated and that the lead-screw assembly is one which remains fixed with respect to the operator's eye.

The weight of large dials (which must be quite rigid to retain accuracies commensurate with 1000 line engravings) as well as space limitations may prohibit direct micron readout facilities on most smaller stage designs. A 2-in. dial can be engraved in 10-micron divisions, which are easily read. Moreover, when the lines are fine and accurately spaced, estimates in 2-micron units are quite feasible. Again, a vernier can be provided, enabling a conscientious operator to read 1- or 2-micron units nearly as accurately (though not as efficiently) as on an 8-in. direct-readout dial. The number of dial revolutions, or millimeters of advance, is usually read from a linear scale mounted parallel to the way guide, and with the indicating pointer attached to the slide.

On stand-attachable and other compact stages a major readout problem is posed by the use of large emulsion sizes. Superplates, or even the emulsions themselves may at times override both dials and linear scales, cutting off the operator's view. Linear scales can usually be repositioned; however, relocating the dial and control-knob unit calls for longer lead screws (at the risk of increased thread warpage) or for coupled shaft extensions. Such extensions exaggerate lead-screw instabilities unless mounted on separate bearings and connected to the screw shaft through flexible, antibacklash couplings. Unfortunately, in-line shaft extensions often place control knobs beyond convenient reach, or dials beyond easy reading span.

Gearing is often used to bring control knobs, readout dials, or both to more convenient operating positions; it also permits the use of rotary digital counters (such as the Veedor-root, Durant, etc.) so that both increments of turn and number of turns may be combined into a continuous row of digits (Fig. 22). Some design problems of geared extensions may best be pointed out through the following example. The X-coordinate dial and linear scale for the L.R.L. scanning stages (p. 42) are obscured by large emulsion sizes. Geared readout extensions are used to actuate a 7-digit instrument counter conveniently located on the stage base plate in line with the Y and Z-coordinate readouts. This is accomplished (as shown in Fig. 23) by using a 1-to-10 ratio spur-and-pinion gear set, a matched mitre-gear set provided with a throw-out clutch, a carefully lapped splined shaft of 4-3/4-in. throw (to allow for Y-axis travel, since the X way assembly is carried by the Y way slide), and a final set of matched mitre gears to permit horizontal digit alignment on the counter unit. The 1-to-10 gearing at the take-off point reduces backlash error by a factor of 10 and permits direct micron units to be read from the 100-division unit drum of the counter. The splined shaft is the most critical component. It must provide an extreme minimum or backlash, and at the

ZN-2440

Fig. 22. A range-measuring microscope developed by the Barkas Research Group, L.R.L., Berkeley. Rotary counters facilitate visual X, Y, and Z coordinate readouts. The X and Y counters, located at the left rear, provide continuous micron-unit readings for the 9- x 10-cm stage travel. The Z counter gives direct $1/10$ -micron readings for the vertical location of the track in the preprocessed pellicle. (A conical-drum drive permits adjusting the counter so that the shrinkage factor is included in the readout.) Lead-screw dials and linear scales are impracticable on large-superplate stages of this type. The Y counter is here geared directly, while the X counter must be driven by a telescoping-shaft arrangement similar to that shown in Fig. 23.

MU-20070

Fig. 23. Method used to drive a fixed X counter where the X way-assembly is carried by a Y way-assembly through 4-3/4 in. of Y travel. Similar telescoping drives are sometimes necessary where heavy or bulky encoding units are to be employed for X-axis digitization.

same time it must telescope precisely along the axis of the Y coordinate without any measurable friction between its mating parts. (The unit is unavoidably located at the extreme "outboard" overhand of an offset X way assembly. Any frictional drag at this point magnifies the coupling tendency of way systems of this type -- as discussed on p. 83.)

8. Evaluating and Correcting Stage Performance

A careful check of each way unit is usually made before full stage assembly. The "feel" of lead-screw moment, of bearing roughness, and measurements of pitch and yaw tendencies of the way slide are best carried out before the unit is loaded with an upper way assembly or an emulsion platform. However, evaluations for each coordinate travel are definitive only when the stage is fully assembled to the microscope and provided with an operating workload. At this point several alignment checks are essential:

- a. The axes of travel for a two-coordinate stage must form an angle of 90 deg with each other (a 1/4-deg tolerance is normally adequate).
- b. The emulsion table or stage superplate must lie in a plane closely parallel to that defined by the way system. In this respect lightweight superplates or frame-type emulsion holders, especially, require careful checking for tilt or warpage.
- c. The plane of the emulsion table, and thus that of the way system, must be perpendicular to the optical axis of the microscope (usually within $\pm 1/2$ deg over the full travel of a two-coordinate stage).

Final checking of the above alignments is best done optically, especially where an axis of travel is defined by mating dovetails rather than squared surfaces. A special stage micrometer such as shown in Fig. 24 is useful here as well as for the task of obtaining critical performance data. It can be used together with the microscope's optical system and a good filar micrometer to measure stage deviations of as little as 0.05 micron. The parallel base-line rulings on the stage micrometer (Fig. 24) aid alignment along a coordinate travel. These and the perpendicular ruling are of course used for checking item (a) above. The full upper surface of the micrometer (or of a thin optical flat) may be used for checking item (b). Surface scratches or a light dye film are kept in focus while peripheral travels are run. Any progressive lowering or raising of the objective necessary to maintain focus will give both the direction and the degree of tilt of emulsion table and stage ways with respect to each other. It should be noted, however, that this check does not assure perpendicularity of either stage axes or emulsion table to the optical axis. Verification of (c) requires a mechanical jig attached to the objective sleeve or to the nosepiece mount to provide a horizontal reference plane.

Stage alignments to other than modest tolerances may seem mere hair-splitting when one considers the distortions inherent in thick emulsions and the warpage of their mounting plates. Nevertheless, where tilt and horizontal angular departures of coordinate travel are corrected, or at least calibrated, to close tolerances, subsequent evaluations with the stage micrometer are greatly facilitated. Some of these will be listed:

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Fig. 24. Partial sketch of a 2.5-mm-thick glass stage micrometer for extended-travel stages, ruled to specifications by Bausch & Lomb Optical Co. This micrometer has a 100-mm scale with 0.1-mm divisions. Width of diamond-ruled lines is 0.003 mm. Length of shortest lines is 0.04 mm. Tolerance on 1-mm intervals is ± 0.0005 mm.

a. Over-all linearity of travel for each coordinate may be determined in the vertical plane by plotting Z readings at exact 1-mm intervals for full travel with the surface of a glass flat kept in focus at considerable magnification. (One-mm, or even-turn screw advances minimize the effect of local noise fluctuations.) In the horizontal plane, filar readings are taken at mm intervals along a certified straight-line ruling of the stage micrometer. Curved plots, rather than essentially linear trajectories, will indicate the amount of way-guide curvature in either plane. While a smooth curve of 10 or even 20 microns' amplitude over 4 in. of travel will have little effect on the accuracy of short track measurements in the emulsion, verification that such curvature exists provides extremely important trouble-shooting data. For example, way-guide curvatures that are convex with respect to a corresponding way slide contact will permit either a vertical teetering or a horizontal snaking of the slide; screw eccentricities and "stick-slip" starting frictions will be readily transformed to stage noise. Again, for way units of known straightness before installation, the above checks will reveal any distortion induced by bolting stage units together, or warpages resulting from molecular growth of guides or mounting castings.

b. Stage noise, or the sporadic local departures from linearity which occur during intervals of stage translation, can be measured as amplitudes of displacement at right angles to the line of travel. This can be done in essentially the same manner as discussed above for the measuring of over-all linearity, except that cell lengths of less than 1/2 mm will normally be used. Precise evaluations of $\bar{D}$ noise through second-difference calculations (see first footnote p. 47) is certainly not mandatory for full two-coordinate travels of most general-purpose stages. Indeed, $\bar{D}$ noise in the vertical plane is rarely calculated, even for the measuring coordinate of a commercial scattering microscope.* However, a selective measuring and plotting of local shifts from linearity in both their vertical and horizontal amplitudes will provide valuable data for evaluating (and for improving) the performance of even stand-attachable scanning stages. Some suggestions and procedures will be listed:

1. Vertical noise measurements can be made with fair accuracy to perhaps 0.2-micron units by using very high magnifications to minimize depth of focus (see footnote p. 15) and by attaching 0.1-micron readout facilities to the fine-focus unit.

2. Precise measuring of horizontal noise increments calls for a line ruling of known straightness. Its edges must be extremely clean cut and sharply defined under 1000x magnification. (Where straightness and perpendicularity of stage micrometer rulings are suspect, a series of readings may be averaged against a repeated series taken with the micrometer rotated 180 deg.)

* This is unfortunate since it is sometimes expedient to measure scattering amplitudes in both the horizontal and the vertical planes. Although depth-of-focus problems lower the precision of measurements of scattering departures in Z, Z stage noise can still be large enough on an otherwise adequate stage to introduce errors into the scattering evaluation.

3. Accuracy of noise measurements taken at right angles in the horizontal plane will be best assured if stage table and ways have been properly aligned to permit a long series of advances with very little readjustment of the fine-focus unit. This minimizes a compounding of fine-focus noise and stage noise for each measurement.

4. Preliminary noise checks can be most effective when readings are taken at consecutive 450-micron cell lengths. Thus, at some reading during a series of 20 intervals, the maximum effect of lead-screw eccentricity will lie precisely along the vertical or the horizontal measuring increment. Where maximum horizontal deflections occur at a point of minimum vertical noise, or vice versa, the carry over of lead-screw defects (eccentricities of pitch diameter or thread drunkenness) is both evident and measurable from a composite graph of the 450-micron-interval readings.

5. While minute increments of vertical noise are not detrimental to filar measurements in the horizontal plane, vertical departures approaching 0.5 micron can be suspected of engendering horizontal fluctuations as well. Vertical noise of slightly greater amplitude will also cause fade-out -- a bugbear of lightweight scanning stages. Fade-out is normally most evident (just as is coupling in the horizontal plane) at the moment of overcoming inertial or stick-slip friction. However, its effect may extend far enough over the field of view (during stage advance) to be mistaken as field curvature of the optical system. The mystery of why some objective-eyepiece combinations give flatter a field of view on one emulsion microscope than on another can usually be resolved by comparing vertical stage-noise amplitudes for the two instruments.

6. Noise directly attributable to stick-slip friction can be isolated from other factors by taking a reading after the stage has been at rest for a minute or so and then another reading immediately after advancing the stage 5 or 10 microns. Off-axis shifts will indicate teetering or snaking of the slide, or more basically, such excessive friction between mating contact surfaces that even a well-seated slide is forced to give.

7. Noise data for a two-coordinate stage will normally vary widely between an upper and a lower coordinate unit. (Y-positioning travels for precise scattering microscopes often have such instabilities that they must be provided with clamping facilities even though they are at rest during scattering measurements.) On a stage designed for measuring in both coordinates, the best procedure is usually to let stand any fair-tolerance noise level for the upper or X assembly and concentrate on bringing the Y noise down to the same range through a careful reworking or realigning of its components. Stability improvements for the lower unit will often reduce noise for the upper coordinate as well.

8. Again, noise for two-coordinate stages of considerable travel will normally worsen as either limit is approached or if one coordinate travel is at an extreme position while the other is being evaluated. Rigorous evaluation thus requires that noise calibrations for one coordinate be repeated for each of several positions (at least three -- central, and each extreme) of the other way slide.

9. Final noise calibration of an X-coordinate stage which is to be used for multiple-scattering measurements requires the customary "scattering" of a certified straight line* through taking readings of Y noise at 100-micron intervals and calculating the second differences of these.† The builder of custom stages should be forewarned that this final $\bar{D}$ -noise figure will be higher by at least a factor of 2 than a figure obtained by merely averaging Y increments of departure. A scattering microscope is only as good as its fine-focus linearity with regard to noise in the Y direction. This can also be determined with a straight-line ruling placed along the X axis of travel, but with the stage micrometer elevated at one end so that the ruling forms an angle in the vertical plane of perhaps 5 to 8 deg with the axis of stage travel. Even increments of X travel will give even cell lengths of Z travel required to refocus the ruling. Second differences of departures in Y are calculated to give $\bar{D}$ noise for the fine-focus unit. Both the above noise evaluations are made even more accurately (and should therefore be double-checked) through use of an interferometer. On some Michaelson types, at least, the mirror or prism component can be attached to the microscope objective mount. Thus, Y deviations for both X and Z travels may be checked with the same set-up.

c. Error of advance for a stage movement is normally quite distinct from the lead error of the screw actuating the movement. The builder of custom stages is often pleased to find that error per centimeter of travel for the emulsion platform (as measured with a good stage micrometer) is actually less than that of the screw itself. However, on closer check he may find that errors of advance for 6,300 or 2,850 microns are actually greater than for a full 10,000 microns; and that in almost every case there will be two positions of the control knob within each turn where local errors of advance exceed the error for an even mm (or full revolution) of the screw. Moreover, amplitudes of these fraction-turn errors may vary widely for different regions of stage travel even though lead error per cm remains quite constant. Some suggestions for evaluating local errors of advance and for isolating their causes will be given:

1. A stage micrometer with certified 100-micron-interval graduations is most helpful. Readout errors may be minimized with a precision-graduated dial and vernier to give $1/2$ - (or better yet, $1/10$ -) micron least-interval readings temporarily replacing any less precise dial on the lead screw. (An even better alternative for small-diameter screws is a light-weight dial with very precise 100-micron engravings; at each dial setting the error with respect to the stage micrometer scale can be accurately measured with a filar micrometer in the eyepiece.)

* A very-high-energy ("minimum") track in the emulsion is often used as a substitute for a ruled line. Here errors due to emulsion distortion will perhaps be no greater than those due to roughness of a ruled line's edges; however, few such tracks will have a dip angle so shallow that fine-focus noise is excluded.

† Second differences of stage noise in the vertical plane may also be calculated (through use of increments of vertical departure obtained as suggested in item 5 above). Thus, the capabilities of the stage for possible use in measurements of vertical scattering will be known.

2. Readings at 100-micron intervals are taken either for full travel or for representative cm sections. Both dial and stage-micrometer readings may be plotted for immediate detection of inconsistency patterns. (The stage-micrometer readings will of course be a straight line unless data for scalar departure from a metric standard are at hand.) The plot of the dial readings will most frequently be a curve of sine-wave form, reaching a positive and negative maximum error with respect to the micrometer plot at half-turn intervals. Thus, a full turn of the dial from any starting point effectively cancels out these periodic errors. Remaining error at full-turn intervals is error of run; this alone is directly related to previously calibrated lead errors for an individual screw, and should be considerably ameliorated through the spanning effect of the drive nut.

3. Much periodic error is due to the same causes as is stage noise; 100-micron-interval noise and periodic-error plots for the same screw positions will normally show similar maximum amplitudes. However, where periodic error is consistently high and noise level low, it is evident that a floating drive nut (or a very loose-fit rigid drive nut) is effectively reducing noise at the expense of firmness against screw thrust along the axis of travel. A compromise adjustment can usually be reached. This, of course, calls for a rechecking of noise for the coordinate.

4. Lead-screw misalignment with the axis of a way guide is indicated by an increase in periodic error as one, or perhaps either end of the thread run, is approached. A consistent periodic error through entire travel will indicate screw bearing-land eccentricity with respect to an otherwise very concentric pitch-diameter axis. (This is often observable on extensively lapped screws where precautions were not taken to lap bearing journals as well. See p. 94).

5. Short intervals of advance on some heavy stage units are subject to stick-slip lead error. Indeed, the stresses induced by a sudden starting impetus may take a full second or more to even out after the control knob is stopped. If readings are taken too quickly the error will be excessive. If one waits for the flexing to equalize, an event aligned to the cross hairs will have crept on past.

6. It should be noted that total error of advance over a distance of several full screw turns plus a fractional turn will involve both periodic and run errors. If both errors are long, or both short of true increment value, they will be additive; if one is long and the other short at the unique measuring point, it is conceivable that they may quite cancel each other out. Thus, unless both these errors of advance are kept extremely small, length measurements as read from a lead-screw dial will be erratic at best, and their definitive calibration nearly impossible.

E. Clamping Emulsion Plates to the Stage Table

Plate-attaching methods will be briefly discussed at this point, since unusual fluctuations of stage noise and measuring readouts are frequently traced to the operator's carelessness in attaching an emulsion plate-- or to the impossibility of firmly attaching it with the mechanism provided. Unfortunately, no fool-proof method has yet been devised for holding larger emulsion sizes both solidly and flat to the stage table while at the same time permitting their quick reiteration and interchange. The problem is further complicated on stages with single-coordinate measuring facilities by the need for optical-axis rotation, and on general scanning stages by the desirability of achieving precise register for successive plates from a stack exposure. Some currently used methods will be listed:

1. Magnetic Chucks

Magnetic (or possibly vacuum) chucks are standard for scattering microscopes and other precision measuring stages using plate-rotating facilities. (See p. 68.) The clamping action can be quite positive, and most important, is accomplished without need for the operator to touch the emulsion, thus eliminating possible distortions from body heat and humidity. Some problems involved are:

a. Each emulsion plate must itself be firmly attached to a soft-iron frame. This procedure is rarely adequately solved. "Plasticene" with its accompanying uncertainties (see below) is normally used. The frames must usually be kept quite thin; they are prone to both warpage and rusting.

b. The magnetic chuck requires special circuitry to achieve a "residual field." Even well-filtered direct current will cause flux vibrations if the magnet remains energized during measuring procedures.

c. The weight of a magnetic-chuck assembly is prohibitive for many smaller stages. The design of the chuck is complicated (especially on extended-travel stages) by the need to retain central clearance for the condenser through full-stage movements.

2. Flat Stage Tables and Plasticene

A plastic clay bearing the trade name "Plasticene" offers the simplest, and perhaps the least dependable, means for affixing emulsion plates to the stage table. The stage platform or superplate needs no restricting protuberances. Emulsions of any size may be orientated at will and quickly stuck down with a pinch of Plasticene at each corner. Problems with this method are:

a. Emulsion plates are never accurately flat; a bowed plate will be temporarily flattened by Plasticene applied firmly at four corners, but will slowly resume its original bow owing to the elastic flow of the putty-like material. Even where two adjacent corners remain firmly attached, the result will be an emulsion-plane tilt twice as great near the loose and as that caused by the original bow. Moreover, instabilities in this region may be such that the cohesive effect of immersion oil between emulsion and objective will cause a "following" action during focusing or vertical measurements.

b. Bits of Plasticene sticking to the stage table may add to the tilt and instability of a subsequent plate installation. Loose particles of Plasticene and the solvents used to remove the material from the stage add considerably to maintenance problems.

c. Plasticene hold-downs do not, of course, provide a means for register of plate sequences.

3. Emulsion-Holding Frames

A frame designed to take a specific emulsion size is frequently affixed to the stage table or directly to an upper way slide. Spring-pressure arms hold the plate against two sides of the frame; milled lands or tab extensions keep the plate from falling through the frame. Various systems for precise register of plate sequences may be incorporated. Some problems involved are:

a. Frames must be tailored to fit each emulsion size used. They must also be provided with reiterating facilities. Here, it is usually necessary that the frame be unbolted from slide or table top, moved to a new location, and bolted firmly once again. Frames for large-sized emulsions are difficult to machine to fair-tolerance flatness; additional warpage is induced where they are bolted down along one side only.

b. The spring arms must apply considerable pressure to hold a large plate firmly in position. Any incipient bow of the plate will be aggravated by this horizontal force; a tendency of larger emulsion sizes to flex or vibrate is often evident, since there is only peripheral support for the entire plate area.

c. Maintenance for microscopes equipped with frame holders of this type has been found to run unusually high. Reiteration of the entire holder prevents effective use of safety stops on stage travels to keep the frame borders from inadvertently colliding with a condenser top. Small glass splinters are dislodged from plate edges by the spring-pressure arms and frequently work their way into stage components.

4. The L.R.L. Dowel-Pin Securing System

Most of the shortcomings of the above-mentioned plate-attaching methods have been eliminated by a system now in use on scanning and range-measuring microscopes at the Lawrence Radiation Laboratory, Berkeley. The stage table is a large-area superplate of 3/16- or 1/4-in. -thick tempered aluminum alloy. The upper surface is unencumbered with clamping fixtures; instead, a pattern of precision jig-drilled and -reamed holes is arranged about the window cut-out. Each emulsion plate is provided with a strip of tool steel glued to the upper surface of the glass along one border of the emulsion. This strip protrudes beyond the plate and partially overlaps a second strip of tool steel provided with a row of jig-reamed holes of identical spacing to those of the superplate. Thus, with the aid of two dowel pins, plates of any size may be quickly attached to the superplate and reiterated just as quickly so that a desired area will fall over the superplate's window. All metal strips have at least three holes (larger sizes as many as five) so that the

possibility of a slightly loose dowel fit owing to wear is easily overcome by inserting a third pin. The two metal strips are designed for mutual adjustment; this permits setting each plate to precise optical register with adjacent emulsions from the same stack exposure.* It should be noted that a system of this type does not in the least restrict the versatility of a flat stage top. Test emulsions or plates not yet provided with metal tabs can be readily attached with Plasticene. Some problems involved in the construction and use of this system are:

a. The dowel-pin holes and the thickness of the dowel-pin tab (the second metal strip described above) must be held to critical tolerances. A master jig-bar with hardened inserts assures precise matching of holes in the steel emulsion tab with those of the superplate as long as all units are drilled and reamed directly from the jig-bar. The thickness of the metal tab is more difficult to adjust, since the bow of larger emulsion plates must be considered if the tab is to maintain the plate as nearly parallel as possible to the superplate and permit some contact with this at other than the tab end.

b. Some breakage with large emulsion sizes (9x12 in.) has been occasioned by the tendency of operators to grasp an emulsion plate solely by its metal tab during handling.

A modified system is now used on 6x9 and larger emulsions: Each emulsion plate is affixed to the top of a metal frame. The adjustable dowel-pin tab is attached to this rigid frame, rather than to the glass plate itself. This arrangement protects the plate, considerably restricts its warpage, and assures that the emulsion plane will lie parallel to that of the superplate.

F. Maintenance for Special Microscope Equipment

The builder usually sees that his custom instrument is properly installed in the operating area. Gear-mesh and other adjustments for prevailing temperatures are made; special shock mounting is used to isolate the instrument from vibrations from adjacent machinery or other sources. A final check-out of stage and optical system assures that the instrument is in perfect operating condition. However, there can be no assurance that it will retain measuring accuracies, optical alignment, and over-all performance efficiency unless an adequate servicing and maintenance program is provided.

*This plate clamping and registering system was devised by Dr. Walter Barkas, physicist in charge of nuclear emulsion research at LRL, Berkeley. It is more fully discussed and illustrated in reference 11.

1. Need for a Maintenance Program

Microscope equipment used in the analysis of large, thick emulsions is subject to far more than normal wear and tear. Scanning procedures quickly add up meters of stage and fine-focus travel. Optical components are inadvertently bumped during the interchange of perhaps a dozen or more awkward-sized plates per operating session. As noted in Section E above, some plate-clamping devices greatly augment cleaning and repair tasks. Long-working-distance objective require heavy applications of immersion oil. Even with normal operator care in "mopping up," this oil ultimately seeps into stage parts; into the substage condenser; and most important, may penetrate to object lens elements, inducing image distortion and eye strain long before the cause is pinpointed, unless frequent and thorough objective testing is carried out.

Way guides, lead screws, and other steel stage components present a serious rust problem unless a protective oil film is periodically renewed. Alcohol and other solvents used by the operator for cleaning emulsion and superplate surfaces accelerate rusting of stage components. The convection currents generated by high-intensity light sources transport an astonishing quantity of dust. Illuminator lenses, diaphragms, filters, and first-surface mirrors require frequent and thorough cleaning.

2. Maintenance Facilities

Maintenance on custom microscope equipment is, of course, best carried out by the same individual or technical group involved in its construction. Service should include full maintenance of the basic microscope as well as the stage. (Commercial concerns which handle the servicing of standard laboratory microscopes at a research center will rarely be familiar with the very critical optical-alignment and fine-focus problems associated with 600-micron emulsion analysis.* Moreover, mechanical repairs for the microscope unit would necessitate disassembly from the stage or transporting the entire heavy and delicately adjusted instrument to a distant repair center. Replacement parts for the emulsion-microscope types most often used are frequently not available as stocked items; the instrument may therefore be several weeks out of service.)

* Problems of coarse-and fine-focus wear and of optical alignment peculiar to emulsion microscopy were discussed on pp. 35 and 61. Standard biological test slides are of little use in ferreting out optical misalignments or mechanical deterioration in the emulsion microscope. The thick nuclear emulsion itself is best used. Evaluations of image quality and of focusing linearity should be made at numerous "levels" through the emulsion thickness and for the entire gamut of fine-focus travel. Familiarity with the light-scattering properties of random background grains, and with the seeming shift of steeply inclined tracks is necessary if false diagnoses and misguided attempts at correction are to be avoided.

Little more than minor adjustments and superficial cleaning can be handled "in the field." A well-equipped maintenance shop is essential both for thorough cleaning as well as for major repairs. Here, the special jigs, lapping equipment, optical- and mechanical-aligning instruments, etc., used in assembly and calibration of the custom instrument can be kept available for periodic performance evaluations and to facilitate major overhauls. Maintenance-shop equipment should also include aids for binocular-body prism alignments and instruments for checking objective performance (lens-collimating and testing equipment, apertometers, etc.). Especially where a battery of scanning microscopes must be kept in full-time operation, replacement parts should be stocked for all microscope and stage components subject to wear or breakage. (Manufacturers will often cooperate in supplying fine-focus units, rack-and-pinion assemblies, etc., not normally available as separate items.)

Equipment for custom-making and installing of reticles will be of great help to a diversified emulsion program (see Section 1-C, 1 and 2). A well staffed microscope shop can give prompt attention to the modifications and auxiliary equipment installations always in demand as research expands to include new pellicle sizes and analysis techniques.

3. Microscope Service Facilities at L. R. L., Berkeley

Maintenance programs often collapse for lack of facilities and funds within the nuclear emulsion group itself. The use of part-time personnel curtails valuable trouble-shooting and emergency repair services. Again, the cost of equipping a maintenance shop is often not justifiable for a limited number of microscopes. In such cases emulsion groups may find it possible to pool their maintenance problems with other research groups using specialized microscope equipment. This approach has proved highly successful at the Berkeley Lawrence Radiation Laboratory.

A centralized microscope service has been established for the entire Laboratory through facilities of the Accelerator-Technician Group.* The extent of the project has warranted a well equipped microscope shop manned by a permanent group of microscope technicians. Services include building custom microscopes and special mechanical stages; making diamond-ruled reticles; handling breakdowns, emergency repairs and modifications; and a strict schedule of maintenance and overhaul for all equipment involved.

* This is an engineering- and research-supporting group similar to mechanical technician groups at certain other nuclear research centers. In conjunction with direct work on the particle accelerators, mechanical designers and instrument specialists among the accelerator technicians are concerned with the building and servicing of experimental equipment for individual research groups. The microscope service program was carefully planned by Mr. Cyrill Orly, Head of the Accelerator-Technician Group, to function as a coordinated extension of these construction and maintenance facilities.

Compact two-coordinate stages, developed primarily for emulsion scanning, have proved equally adaptable to other research programs; this has permitted quantity manufacture and assembly of stages at a much lower cost per unit. Through the servicing of a wide variety of specialized microscope equipment for the biophysics and nuclear chemistry departments, the microscope shop is able to evaluate unusual mechanical and optical features for possible application in other fields. Owing to this, a number of innovations have already been built into emulsion microscopes. The program has indeed been advantageous to all research groups concerned.

VI. DIGITIZING THE EMULSION MICROSCOPE

Automation for at least some track analysis procedures is becoming more and more essential to efficient emulsion microscopy. Efforts to replace the observer with automatic scanning devices have met with very limited success to date. On the other hand, automation designed to aid the observer in reading out, recording, and evaluating raw data has proved highly effective. In particular, a tremendous speedup in range, scattering, and other track evaluations directly dependent on linear or angular measurements has been obtained through the use of analog-to-digital conversion devices. Such devices are now commercially available, complete with all necessary electronics to provide direct decimal printout. Digitizing the emulsion microscope, then, may require little more than the fitting of suitable encoding devices to its measuring travels. However, this in itself is frequently a difficult (and sometimes an impracticable) undertaking. The problems involved will be discussed in some detail. They may warrant careful consideration if the readout is to be dependable and if the inherent measuring accuracies and general operating performance of the microscope are not to be jeopardized.

A. Advantages and Limitations of Analog-to-digital Systems

"Digitizing" should not imply a general automation in readout and recording of emulsion data. Grain-count totaling, time-lapse length measurements, automatic readout for photocell track scanning, etc., may require additional, or entirely distinct, recording devices. As here defined, digitization is only applicable to analysis procedures involving variable increments of linear or angular measure. At present, moreover, it is only applicable to the emulsion microscope whose measuring increments (linear as well as angular) are available as a function of shaft rotation. *

Suitable digitizing systems will be capable of "printing out" discrete measuring increments in decimal-digital form. This gives the following advantages:

- a. Primary measuring data can be recorded as much as 100 times more quickly.
- b. Eye fatigue accompanying transfer of focus from a field-of-view at infinity to variously positioned dials and linear scales is eliminated.
- c. Human error in reading graduation marks and in transcribing long sequences of numbers is also avoided.
- d. Where the inherent accuracy of the measuring travel permits, a digital encoder can be selected which will read out in smaller least-increments than the best dial and vernier combinations obtainable.

* When models more suitable for emulsion microscopy are available, the Fer-ranti and possibly other linear digitizing systems will be exceptions to this.

e. Finally, and most important, a digitizing system which can print out in decimal form can just as readily prepare data for (or feed it directly into) standard data-processing machines for its automatic reduction and evaluation.

Digitizing equipment is costly, intricate, and often extremely bulky. Components will include one or more shaft-position encoders mechanically attached to the microscope, a translator unit which is fed electric impulses from the encoder through a cable, and a printing-out mechanism. Depending on the encoder design, the translator may be a simple bank of relays; or it may be a complex of electronic circuits for converting true binary, binary-decimal, reflected-binary, or other special codes to decimal form. Additional circuitry may be necessary to sense changes from increasing to decreasing count, and for amplifying impulses to the wattage requirements of a print-out system. Printing out, if only raw data are desired, may be handled by registers furnished with some makes of digitizers, or by electric typewriters. More frequently, the raw data are printed on a tape-punch (often available with the digitizing equipment) or on a standard IBM card-punch along with emulsion shrinkage factors, indicative information, etc., for subsequent computer processing.

It is often important that data be calculated during or immediately after an analysis procedure to permit comparisons, or rechecking. This has been accomplished at several research centers through the use of custom-built digitizer-computer systems. Such devices often avoid the complexities of full digital translation by means of computer circuitry tailored to the specific encoding sequence.¹⁹ The dearth of commercial electronic computers for individual group use and the tremendous task of custom-building units of fair versatility have limited direct data reduction to quite straight-forward procedures such as multiple-scattering evaluations. (Here, a single, limited-range encoder may be sufficient, and computations are mainly those of taking second, or perhaps third differences normally within the capabilities of an electric calculator.)

At present, the digitizing of stage coordinates and of the fine-focus unit for automatic print-out of range measurements (or other procedures concerned with the precise location of points in the emulsion volume) is best accomplished through suitable commercial digitizing equipment, designed for card- or tape-punch setups. Data processing can then await time-scheduling on an IBM-650 or similar computer that is fully adequate for the task.

B. Suitable Digitizing Equipment

At least ten manufacturers of digitizing equipment now offer models with possible applications to emulsion microscopy.* New designs and improved models have been appearing so frequently (owing mainly to demands of rocketry and other airborne applications) that one is in danger of purchasing a cumbersome, high-torque encoder only to find that this has been superseded by a miniaturized model of equal or better performance. Specifications for the encoding unit will in most cases determine the equipment's suitability for a particular microscope application. However, experience has shown that translator units are responsible for most of the lost-time and maintenance problems on digitized instruments. Unfortunately the most precise, compact, and generally suitable encoding units are designed for special binary-code outputs (compatible with airborne-guidance and machine-automation equipment). Translators for converting certain of these codes to decimal output require extremely complex logic circuitry; those provided often appear to be improvised to accommodate a market of secondary importance.† Some encoders, however, give direct decimal output; no auxiliary translating circuitry is required. Excessive weight, limited, readout range, and high input torque often prevent their application to emulsion microscopy.

The builder of custom microscopes has the advantages of designing around preselected digitizers. Fitting existing instruments with suitable shaft encoders is often much more difficult. Basic considerations are: (a) that the digitizing system provide both the least-increment resolution and the digital range (total number of positional counts) necessary for effective readout of each measuring travel; (b) that the system's encoding units can be mechanically coupled to the microscope without endangering stage performance, optical system stabilities, or the easy access to, and low-torque operation of manual controls.

With a few possible exceptions, encoder choice is restricted to devices operating from rotating-shaft input. They must be directly connected to stage lead screws, filar screw, or other rotating mechanisms of the microscope. Normally such encoders contain a shaft-mounted disc precisely segmented into some optical or electric-contact code pattern. Contacting brushes, photoelectric scanners, magnetic-flux pulsers, or even more

*The following trade names are listed for reference: (The reader may recognize some among these as having proved unsuccessful in past applications. In most cases, however, new and improved models are now available.) Giannini Datex, Baldwin, Coleman Digitizer, Gurley, Librascope, Wang, Electro-Mec Digitometer, Optisyn (Dynamic Research Corp.), Norden-Ketay Digital Converter, Colorado Research Co. Angle Encoder, Litten Industries Shaft Encoders, Ferranti Digital Measuring System.

† See reference 20 for a comprehensive survey of codes used in digitizing equipment, including special self-checking and self-correcting codes, and of translator circuit requirements.

exotic methods may be used to "sample" the code segments. Simple "on-off" segments around the periphery of the disc provide only sequential counts. More frequently, unambiguous readouts (i. e.) unique code signals for each resolvable shaft position) are provided for by several concentric rings of segments covering the disc surface and by one or more brushes or scanners for each ring. Resolvable shaft positions may be as few as 10 per revolution for certain direct-decimal encoders; or as many as 100,000 per revolution (on a recently-available Baldwin disc). It is evident that a 10-count encoder would have to be geared 100 to 1 with a 1-mm pitch lead screw to permit micron-units of readout; furthermore, the count would merely repeat itself every 10 microns of travel. A 100,000-count per revolution encoder would seem ideal for certain stage-coordinate applications. Geared down to 1 turn per 100 lead-screw turns, it would give micron-interval readouts over a full 10 cm of travel. However, gearing problems and the considerable bulk of such a unit may restrict microscope stage application. (Similar Baldwin encoders have 12- to 16-in. -diam discs. Additional housing size is necessary to include some 16 photoelectric scanning units for the several hundred thousand segments required to give 100,000 unambiguous positions.)

Where external gearing is used, gear accuracy must normally be better than the order of encoding accuracy desired. (For a 1000-position encoding disc, the sum of manufacturing errors for each gear plus backlash between gears must total less than $1/3$ deg of angular error). Thus, it is normally advisable to select those encoders which can be direct-coupled to a lead-screw shaft extension, and which provide for extended range through a bank of internally geared encoding discs. Here the encoding pattern can be made to absorb any error or backlash in gearing between units. For example, one model of the Coleman direct-decimal digitizer employs six decade-banks, each geared 10 to 1 with the preceding decade-bank. Shaft connections are provided for at the units, tens, or hundreds decade. If a stage lead screw is directly connected to the hundreds decade input, unambiguous micron-interval readings are available through 99.9999 cm of travel. However, torque requirements for geared-up disc banks (especially of the brush-contact type) are excessive for most microscope applications.* One Giannini Datex model overcomes this problem with a special-binary-coded 1000-count initial disc and a 100-count down-geared second unit. With the primary disc direct-coupled to the lead screw, micron-unit positions through 9.9999 cm are available. This Datex encoder has been successfully used on a number of emulsion microscopes. The latest model (model 703) has encoding discs and gearing integrally mounted in a compact 3-in. -diam housing. The special binary codes of Datex digitizers, however, call for translators of considerable complexity. Judging from installations at the Lawrence Radiation Laboratory, these are not always trouble-free.

*Continuous readout for the Coleman model described requires 100 in. -oz of torque to turn the 100's position input shaft. However, an ingenious solenoid mechanism is incorporated so that brush contacts may be made only during "on demand" readouts (when rotating units are normally at rest). Torque during running operation is thus reduced to about 1 in. -oz.

Photoelectric disc-scanning encoders eliminate brush-induced torque and the problems of wear and corrosion of both brushes and contact points. These encoders are manufactured as single-disc units of high precision by Baldwin, Gurley, Wang, Dynamics Research Corp., etc. Unfortunately, even where multidisc units are available, these are internally geared-up, rather than down; this greatly increases resolution for a single turn, but does not provide for counting more than one revolution of the input shaft. Thus, currently available photoelectric (or other scanning-type) encoders call for external gearing, and in some cases, fabrication of a translator unit to obtain decimal-form readout, or of amplifier circuits to facilitate card or tape printouts.

The Ferranti digital measuring system is perhaps the most successful device for presenting small increments of true linear travel in digital printout form. Here, lead-screw errors, gearing, shaft coupling, etc., are eliminated. The pickup is optical and therefore friction-free. The basic principle of the Ferranti system depends on the production of a Moire fringe pattern. A grating finely ruled on glass accomplishes this. The pattern is read by four electro-optical units, canted with respect to the grating lines. Thus $1/4$ as many rulings as readout counts are required. Up to now, maximum resolution has been in 4-micron units. A 2,500-line-per-cm grating, permitting 1-micron unit readout, is projected.

The present 4-micron least-increment count, the difficulty of attaching the encoding units to Z or to filar travels, and the high cost of the Ferranti system (owing to the precision gratings and extremely complex electronic circuitry) have all forestalled emulsion microscope applications to date.

A note might be added to the selection of digitizing equipment. Many analog-to-digital systems are primarily designed for applications quite distinct from those of the emulsion microscope. The seemingly exorbitant cost of certain designs may often be traced to special provisions for "on-the-fly" readouts. These require exacting sensing devices in the encoder and elaborate storage and "dumping" facilities in the translator. Since on-the-fly readouts are rarely essential (or rarely permissible) in the crosshair-aligning procedures of emulsion track measurements, it is often well to so advise the manufacturer of a tentatively-selected unit. A similar encoder model, and a far-less-complex translator unit may be available at considerably less cost. Moreover, where several microscopes are to be digitized with the same type encoders, it is often feasible to channel all encoder outputs to a single translator (often at a savings of from \$500 to \$1000 or more per bi-passed translator unit). Such multiple-encoder hookups are discussed by W. H. Barkas on p. 6 of reference 11.

C. Installing Shaft-Position Encoders

Certain variations in design often determine whether a particular microscope or stage component can accept encoding devices, or whether digitization is not at all practicable. Stand and stage variations have been discussed at some length in this report. In order not to repeat much background data, page references to pertinent component description will be made from time to time.

1. Direct and Geared Encoder-Shaft Couplings

Direct-coupling does not imply a rigid connection between the measuring screw and the encoder shaft. Indeed, rigid connections are in most cases to be avoided. This is especially important where the encoder shaft serves as a mount for a small-diameter, high-resolution disc. Such discs function near the tolerance limits of ultra-precision bearings. Damaging loads will be exerted by small eccentricities of the screw shaft, by an inaccurate coupling sleeve, and particularly by any misalignment between the shafts caused by slight errors in placing and bolting down the encoder. Eccentricities of 0.001 in. or angular misalignments of a few minutes of arc, carried over to a 1000-position disc, can induce periodic reading errors of several digits in amplitude.

Again, shaft misalignments may be carried back by rigid couplings to endanger the original measuring travel. Filar screws are normally bearing-mounted at only one end; often stage-coordinate screws are similarly designed (see p. 89). A misaligned encoder shaft which has been rigidly coupled to either end of such screws can produce the same effect as extensive pitch-diameter eccentricity on stage and filar measuring accuracies. The result is readily noted on filar units--where the micrometer screw is delicately supported at best. As measurements are taken, the filar hair can be seen to wobble from side to side (identical with stage noise), and to advance in uneven spurts (periodic error of advance).

Flexible couplings can be used to absorb individual shaft eccentricities as well as radial and angular misalignments of the two shafts. Damaging off-axis loads on microscope and encoder components are averted. Such couplings must of course be of an antibacklash type. Where considerable misalignment is present, even these will introduce a periodic lag and lead of disc position since a sort of "eccentric-cam-action" is engendered between the offset axes of rotation. Thus, at two positions per turn a high-resolution disc will read either more or less than the true reading obtained when the two shafts are aligned to precise concentricity. With this reminder that flex-couplings also demand careful shaft alignments, several suitable types will be listed:

a. Long, thin shaft extensions (quill shafts) are effective where the lead screw is solidly mounted at both ends and where readings are taken only "at rest" so that any torsional flexing of the quill-shaft coupling may come to equilibrium.

b. Antibacklash Oldham couplings (and similar types) are more versatile than quill shafts; they are now commercially available in "precision" grades.

c. Simple spring bellows (sylphons) are the most widely used flexible couplings; the great variety of diameters, wall thicknesses, etc. permits their use for both heavy-stage screw and delicate filar couplings. Where convolutions are kept to a minimum and wall thicknesses are commensurate with torque, they are quite backlash-free.

d. The Farrand bellows coupling and other multiple-bellows-and-concentric-tube arrangements have been worked out to give maximum fidelity of input shaft and encoder-disc rotation. These complex couplings are usually not essential for microscope digitization. Details of the Farrand coupling are given on p. 76 of reference 20.

A geared coupling between measuring screw and encoder shafts is usually frowned upon where maximum reading accuracies are concerned. However, a single set of Class-II (or better) precision spur gears, preferably of split antibacklash type, can be used for the following purposes:

a. To permit offsetting the encoder when it is found to interfere with actuating knobs or structural components of the instrument.

b. To obtain (within strict limits) the same results as a flexible coupling. Slight misalignments and eccentricities can be compensated for through the spring-loaded mesh of gear teeth as long as readings are taken "at rest."

c. To down-gear many current encoder types which have a very high digital count per revolution but too short a total range for the travel which is to be digitized.

Large gear diameter will reduce manufacturing errors in tooth-to-tooth spacing and in pitch-diameter concentricity. A fine pitch reduces roughness of tooth mesh and the possibility of resulting vibrations being transferred to the stage or optical system. Gearing-down can greatly reduce torque requirements for the encoder. Gearing-up will of course increase torque requirements and may pose an additional problem--that of reflected inertia from a fast-spinning encoder disc. This can be great enough to cause low-friction filar and fine-focus controls to "overshoot" a positioning point.

2. Digitizing the Filar Micrometer

The filar micrometer and other measuring devices attached to a binocular or monocular eyetube pose two awkward problems: (a) Such devices (except for goniometers) are designed for readings of drum-dial increments through a range of some 10 to 50 drum-dial revolutions. This calls for either an encoder with two or more discs (adding both weight and bulk) or else the external gearing of a single-disc encoder of several thousand counts to the micrometer screw. (b) Those conventional stands most suitable for emulsion

work will have coarse-and-fine way systems which support and actuate the overhead optics (see p.35, item e). The same will be true of custom microscope designs using a coarse-and-fine limb (p.62, item b). Thus, the encoder must ride with the overhead optics if it is to be directly coupled or geared to the filar screw. A bulky encoder is hard to reconcile with frequently-racked coarse-focus controls; a heavy encoder will certainly overload the fine-focus mechanism to the point of exorbitant wear, excessive noise, and unreliable measurements.

Fortunately, filar digitizing is rarely essential on other than scattering microscopes. Most commercial scattering and "universal" microscopes can readily be fitted with filar encoding units of considerable bulk and weight owing to special fixed eyetube designs (see Section IV). The Koristka MS-2 and R-4 models mount both filar and Pothstrilino micrometers on detachable monocular tubes. This presents a disconnect problem for the encoder (since it cannot very well be mounted on the tube itself). The difficulty has been solved on a digitized Koristka MS-2 at Lawrence Radiation Laboratory (Fig. 25) by means of a multijaw disconnect coupling used in conjunction with a sylphon bellows. This combination couples a Datex-703 encoder (1000 positions per revolution $\times$ 100 revolutions) with a Koristka filar-micrometer screw of 36 turns and with drum graduations of 50 units per turn--representing 0.05-micron units at standard scattering magnifications. The particular encoder has far greater capacity than essential for this application. However, its ratio of 1000 angular positions to the 50 positions on the filar drum enables scattering departures to be measured in 0.0025-micron least units.

On commercial or custom microscopes where filar units must move with the focusing controls, one of the following encoder hookup methods may be possible:

- a. direct eyetube mounting of a gear-coupled, light-weight, single-disc encoder;
- b. attaching the encoding unit to the control knob of remote control drives (see pp. 66 - 68.
- c. counterbalancing and "beefing-up" coarse-and-fine mechanisms for direct coupling of a minimum weight two-disc encoder.

3. Digitizing the Z-Coordinate Travel

Most emulsion microscopes will be equipped with a low-positioned fine-focus control to which shaft encoders of almost any type may be directly coupled. Installation is thus quite straightforward. However, a few suggestions might be helpful:

- a. It should be verified that the focus control converts equal segments of linear travel into equal segments of rotational arc throughout the full travel to be digitized, and that the actuating mechanism is essentially backlash-free (p. 35).

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Fig. 25. A Koristka MS-2 microscope with following modifications: (1) A datex shaft encoder (model 703) attached by means of a multijaw coupling and disconnect clutch to the filar unit; (2) A wire cable and sheave system for remote filar control; (3) A fabricated insert (the section of the microscope arm bearing the serial no.) adding 4 in. to the throat.

b. The range (100 positions per turn plus some 20 turns) of most fine-focus units creates the same awkward problem in encoder selection as does the filar unit. Where micron-unit readouts are deemed adequate, a single-disc, 1000-positions encoder may be geared down 1-to-10. This gives the usual 100-micron-unit readings over a somewhat restricted range of 10 turns. However, where full Z travel is desired, or where 1/10-micron-interval readings are essential (for multiple-scattering measurements in the vertical plane, etc) a direct-coupled two-disc encoder is usually the best solution.

c. Low-torque manual operation of the fine focus is essential for efficient emulsion scanning. This problem deserves careful consideration when selecting an encoder, since normal operating torque will be more than doubled with the installation of any currently available two-disc, brush-type encoder.

d. As previously stressed in this report a fine-focus mechanism on the emulsion microscope is subject to unusually heavy wear and tear. Any encoder attached directly to the fine-focus lead-screw mechanism should be precision-aligned and flex-coupled to minimize additional loading of the bearings and to prevent distortions of the focusing screw or gear train.

4. Digitizing the Y-coordinate Stage Travel

The Y-coordinate lead screw usually remains spatially fixed with regard to the stage base. Only on special stage layouts will there be any difficulty in installing an encoder. Two such instances will be mentioned: (a) Where but one shaft-end of the lead screw is available (as in divided-way Y assembly designs discussed on p. 75), considerable gearing may be required to position the digitizer so that it will not conflict with the operation of the control knob and with the operator's torso. (b) The Y coordinate carries most of a stage's weight; torque needed to actuate its lead screw frequently borders on the maximum for operator comfort. A multidisc brush-type encoder may add enough drag to make manual operation difficult.

5. Digitizing the X-coordinate Stage Travel

Direct-coupling to the X screw of a two-coordinate stage requires that the encoder ride along with the X assembly. This poses little difficulty on base-mounted stages of fairly massive design. However, on stand-attachable stages it is often impracticable for a Y assembly to support both an X way assembly and a digital encoder of even modest weight. In such cases, the only alternative is to base-mount the encoder and couple it to the X lead screw by means of a telescoping drive-shaft. (An arrangement similar to that shown in Fig. 23 may be used, except that the only gearing normally required will be a single set of mitre gears). Telescoping-shaft couplings have been successfully used for the X-coordinate digitization of several Lawrence Radiation Laboratory microscopes. One such installation is fully described in reference 12.

Telescoping X-encoder drives, or similar expedients, will be required for most stand-attachable stages of commercial manufacture (Section III-A and B). Attempts to digitize stages attached to the Leitz Ortholux and to numerous other stage-focusing microscopes (see Section II-B and C) may involve complicated telescoping-shaft and universal-joint couplings for both the X and the Y coordinates. Such problems will of course be greatly alleviated as compact, lightweight encoders of suitable range become available.*

A final word about backlash in shaft-encoder installations may help to clarify the somewhat casual references to gearing, telescoping shafts, etc., as applied to stage coordinate digitizers. Since filar micrometer units and fine-focus mechanisms are designed to function backlash-free, it has been stressed that encoders attached to these units must be provided with essentially zero-backlash couplings if reading accuracies are to be maintained. On the other hand, backlash is both present and readily detectable in stage coordinate travels. (Certain designs do incorporate spring-loading or weighting to eliminate backlash; these stages are rarely digitized due to various other inadequacies). On most stages, the operator eliminates primary measuring errors by "taking up the backlash." At the same time he will be taking up backlash in the digitizer couplings. Thus, it appears quite evident that backlash between leadscrew and encoder need only be less than that between lead screw and drive nut (or the movable stage component) to preserve full fidelity of read outs. Thus, presupposing the customary 10 microns minimum of backlash setting for most efficient stage operation (see footnote, p. 99) the special gearing, telescoping shafts, etc., needed for attaching a stage-coordinate encoder, will not endanger reading accuracies as long as its total backlash is held to less than 3.6 deg of arc. (Precision gearing is, of course, still essential; take-up for backlash does not take up for manufacturing errors in gears.)

As a last expedient where backlash from a complicated encoder coupling remains excessive, it again appears reasonable that the fit between drive nut and lead screw could be loosened until a slightly greater backlash than that of the encoder coupling is obtained.

*The Datex-703 encoder has simplified digitization of the L. R. L. large-plate scanning stage. It is light and compact enough to be directly coupled to the X lead screw; no telescoping-shaft device is necessary. The Livermore Lawrence Radiation Laboratory emulsion group headed by Dr. Stephen White has completed digitization of eight of these stages mounted on standard Bausch and Lomb microscopes (Fig. 26). Three Datex-703 shaft encoders provide full X, Y, and Z coordinate readouts for each instrument. Information is printed out by means of standard Datex translator and tape-punch equipment.

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Fig. 26. Application of digital encoders to a conventional-microscope-mounted stage. The instrument shown is one of eight identical units developed by the Dr. Stephen White nuclear emulsion group at L.R.L. Livermore. It accomplishes fully automatic tape-punch printouts (suitable for IBM computer processing) of X, Y, and Z coordinate measurements in the emulsion. Microscope: Bausch & Lomb "Dynoptic;" Stage: modified L.R.L. large-plate scanning (10×10cm); Digitizing: three Gianni Datex model-703 shaft encoders, Datex translator and tape-punch.

VII. ADDITIONAL NOTES ON AUTOMATION

Digitization has already established itself as a worthwhile permanent asset to emulsion microscopy. This cannot be said of numerous other approaches to automation, even though prototypes of these may have antedated by five to eight years the first three-coordinate digitized microscope.* Various devices to facilitate automatic track scanning have been built and their innovations discussed in scientific journals. (These include perhaps a dozen experimental microscopes for measuring track ionization with the aid of photoelectric image-scanning devices.†) However, upon attempting to evaluate the subsequent application of these instruments, one finds that few have outlasted initial experiments.

Reasons for the transitory success of much automatic equipment are aptly given by W. H. Gibson.²¹ He deduces that few research groups are capable of converting an experimental apparatus into an instrument adequately designed for use by the group's scanning personnel. (This point has been stressed throughout the present report. The reader may recall specific references in part C of the section on Custom Designing, and on p. 55, item 5.)

Gibson notes lack of flexibility as a second major factor which has discouraged the retention of automatic apparatus for general use. Mechanical scanning devices, in particular, have heretofore been capable of little more than a single discriminating task per instrument--and this often further restricted to a narrow range of emulsion thicknesses and densities.

However, earlier difficulties with unwildly electromechanical equipment and pre-transistor-age electronics are now greatly ameliorated. The same impetus towards precise, miniaturized guidance automation for airborne use, which has been so helpful in digitization, is making commercially available such items as servo drives, resolver systems, television scanners, ultra-sensative photomultipliers, etc. Access to such components, constructed for maximums in accuracy and compactness, may well permit the combining of several automatic procedures in a single microscope of manageable proportions.

*The L. R. L. range-measuring microscope described on p. 56 can perhaps claim distinction as the first fully digitized microscope. It has been in continuous service since the early part of 1958.

†The use of photometry for grain-density measurements has not, in many cases, been undertaken for the purpose of automation speed-up, but rather to accomplish measurements which are difficult, and sometimes impossible by means of the human eye alone. Indeed, many such devices operate at a much slower pace than comparable grain-density apparatus using visual image surveying and semiautomatic readout equipment. It is evident that track-ionization work by either method can in most cases be greatly speeded up by adding two- or three-coordinate digitization to existing semiautomatic features.

Unfortunately, a third problem not mentioned by Gibson has marred the success of most automation dependent on photoelectric scanning of the image. This includes track-width and grain-gap measurements;* emulsion sweeping for determining angular and range distribution of tracks, frequency of events, etc.;† and all proposed methods for automatic track following.‡ To date, automation of this type has depended on photomultiplier response to discreet variations in the amount of transmitted light obscured by ionized grain blobs, or, in the case of higher energy tracks, by minute individual grains delineating the particle's trajectory. The problem is that light intensity reaching the photomultiplier varies not only with the track density itself, but with other factors which are difficult to control and often unpredictable. Contrast drops rapidly as the emulsion layer between track and microscope objective increases in thickness; light intensity will vary with emulsion types or even with individual emulsion batches; it will fluctuate within a single pellicle owing to uneven processing, to fogging, spurious radiation, etc. Variations in intensity great enough to invalidate measuring data have been traced to the lines of grids which are often lightly printed on the under surface of the pellicle for coordinate reference.§

While these variations are most detrimental to photometric measurements involving relative densities (track densitometry), they also cause serious problems for "cut-off" scanning systems. Here, very narrow scanning slits are normally used to restrict the field of view so that a grain blob or track segment in focus obscures all light reaching the photomultiplier. Scattering from background grains above the track makes it impossible to achieve total obscuration from even heavy tracks located perhaps a hundred microns or so beneath the emulsion surface. At still greater depths, contrast between higher energy track grains and the general background may well fall below the actuating threshold of a sensitive photomultiplier.

* An excellent discussion of the advantages and limitations of track photometry for grain-density measurements is given by C. F. Powell, et al. in ref. 22.

† An instrument of this type is described on p. 56, item 7. See also the "flying spot" microscope proposed by J. G. McEwen and J. Herbert in ref. 23.

‡ See, for example, the proposed system discussed in considerable detail by M. J. Duff in ref. 24.

§ This and other problems encountered in the use of a track photometer for measuring slow particle ionization are discussed by F. W. Inman: "The Analysis of Hyperfragments from Strange-Particle Interactions," UCRL-3851, pp. 44 - 52 (1957).

Numerous experimenters have made efforts to overcome these optical problems. Van Rossum and others employed modified substage optics (in particular, rectangular condenser stops) to obtain greatly reduced variations in image contrast with emulsion depth.²⁵ Minute, oscillating pencils of light, darkfield illumination, and polarization have been investigated.* Some additional improvement still seems essential before automation of the emulsion microscope can be expanded to include reliable track-width and grain-gap photometry for representative 600-micron emulsions. Considerable improvement in image contrast control is definitely necessary before automatic emulsion surveying and automatic track following can be successfully applied to typical emulsions in this same thickness range. Anything approximating a fully automatic general-purpose microscope may require scanning systems entirely divorced from conventional microscope optics, maximum uniformity of emulsions, and a complex of electromechanical positioning and electronic discriminating devices far beyond the present capabilities of most research centers.

The growing backlog of partially scanned emulsions and perhaps the continuing effectiveness of photographic emulsions as a major research tool demand that automation of the emulsion microscope proceed apace. Yet the designer, confronted by the above-mentioned problems, must proceed cautiously with efforts to combine automation for several analysis procedures in a single instrument.

"..... et mon sentiment c'est que si on essaie de réaliser un machine capable de tout faire on aboutira peut-être à une machine qui ne fera rien d'utile." 21

* Investigations are now in progress at the Lawrence Radiation Laboratory as to the feasibility of using darkfield illumination with thicker photographic emulsions. Results to date are disappointing. With standard darkfield optics all ionization save that of fully saturated tracks becomes indistinguishable from a strongly luminescent background at emulsion depths of 150 microns or greater.

A UCRL report: Specialized Optics for Emulsion Microscopy is planned concurrent with the completion of these and other investigations of special illumination; reflecting objectives; visual, film, and televised projection scanning, etc., as possible aids to increased efficiency in emulsion analysis.

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