Seed quality is determined by attributes or traits that can be grouped into four categories: GENETIC factors - mainly, trueness-to-variety; PHYSICAL factors - attributes ranging from the traditional "purity" components to the incidence and severity of mechanical damage, to seed size; PATHOLOGICAL factors - type and incidence of seed borne diseases; PHYSIOLOGICAL factors - germinability, vigor. All of the categories of factors are important in the essential quality assurance "business" of a seed company and merit detailed discussion. Here, however, the emphasis will be given to PHYSIOLOGICAL SEED QUALITY.

What is Physiological Seed Quality?

The first and most crucial milestone in field and vegetable crop production is successful establishment of a uniform stand of vigorous plants. The degree to which this milestone is achieved has a great influence on the profitability of crop production. Crop stand establishment is mainly affected by two factors and their interactions: physiological quality or vigor of the seed planted and the microenvironmental complex of the seed bed.

Physiological Seed Quality

Physiological seed quality comprises those intrinsic attributes of seeds which determine their capacity to germinate and emerge rapidly and to produce a uniform stand of vigorous plants under the range of field conditions that can be encountered at planting time. Since the function of crop seed is propagation of the crop and fulfillment of this function requires that the seed perform in specific ways under greenhouse and field conditions that can vary over time and among locations during the planting season, physiological seed quality can, perhaps, be most easily conceptualized as the performance capabilities of seed.

The performance capabilities of seeds are maximum at the time they attain physiological maturity, which is usually some days before harvest. Thereafter, the performance capabilities of the seed—their physiological quality—are inexorably, irreversibly, and progressively

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1Professor, Seed Technology Laboratory, MSU. Article based on paper published previously.
eroded by processes termed deterioration (also aging, degeneration) which are common in all living systems and culminate in death. While deteriorative processes in seed are inexorable, their rate is strongly influenced by the climatic conditions that prevail in the seed field before and during harvest and the specific practices used to harvest, condition, store and distribute seed for marketing to producers. Thus, the physiological quality of a seed lot at any given time is essentially determined by the extent to which the individual seeds in the lot have deteriorated.

Deterioration of seeds is progressive, and its consequences in terms of effects on seed performance capabilities are sequential and increasingly serious. The fundamental deteriorative changes occur at the cellular or sub-cellular levels and affect the integrity, functional capacity, and efficiency of nuclear materials, organelles, membranes, and biochemical mechanisms that control and "drive" the physiological processes required for seed performance. At the seed--or seed response--level the consequences of deterioration are manifested as a progressive reduction in performance capabilities.

The final and most serious consequence of deterioration is death, which for crop seed can be equated with loss of the capacity to germinate (Figure 1). Before this final state is reached, however, a sequence of lesser consequences arise during deterioration which impair other aspects of performance--other capabilities--that are important in crop stand establishment and production. The lesser consequences of seed deterioration will be considered later in this discussion.

Germination Percentage

Germination percentage is the most widely used and recognized index of physiological seed quality. It is determined by standardized tests developed and refined over the past 100 years. Yet, even at the beginning of organized seed testing, it was recognized that germination percentage had limitations as the index of the stand and plant-producing potential, or field value, of seed. These limitations have become increasingly clear and more serious with advances in crop production technology (and costs of production) and our knowledge of seed physiology.

The deficiencies of germination percentage as an index of the performance capabilities of a seed lot in crop production stem primarily from the test methodology that has been evolved to establish germination percentage, and the aspect of performance the test assesses. Germination tests are made under conditions that are rather "artificial" and highly optimal for the level of seed performance to be assessed, i.e., capability of the seed to germinate and develop into a "normal" seedling. The near ideal conditions of the test and
Figure 1. Possible sequence of changes in seed during deterioration.
long test periods permit seeds that are relatively low in physiological quality to perform to an acceptable level and thus to be "counted" in the computation of germination percentage. The germination test, therefore, essentially establishes the proportion (%) of seeds in a lot in which the final consequence of deterioration is not yet manifest, i.e., loss of germinability. The test provides relatively little information on the progress of deterioration (lesser consequences) which, since few farmers knowingly plant low germination seed, really determine the capabilities of the seed to germinate and emerge rapidly and to produce a uniform stand of vigorous plants under conditions that are frequently far from ideal.

Although germination percentage has serious limitations as an index of the field performance capabilities of seed, it is a very useful index of seed quality for routine assessment of seed lots for their suitability for used as "planting" seed, the regulation and control of seed marketing, and other "business" purposes. No one advocates abandonment of the germination test. Rather, the growing trend is to supplement the base information provided by the germination test with that obtained from other, more sensitive in-house tests, which do evaluate the physiological status of seed lots.

Some Effects of Physiological Seed Quality On Crop Production

The final phase or consequence of seed deterioration is manifested as a decrease in the germination percentage of a seed lot. It is easily established by a germination test. However, the lesser consequences of deterioration which affect the performance capabilities of seeds are not very evident in the results of a germination test. The lesser consequences of seed deterioration include a reduction in the rate and "intensity" or "vigor" of germination, emergence, and plant growth and development, and an increased sensitivity of the seed/seedlings to environmental conditions during the period of stand establishment.

Emergence and Stand Establishment

Physiological seed quality has its greatest and most incontrovertible effect during the emergence and stand establishment stage. Seeds of high physiological quality have the capability to germinate and emerge rapidly and uniformly -- especially important in the case of vegetable crops -- and to develop into a stand of vigorous plants under a wide range of field conditions. While use of seeds of high physiological quality does not "guarantee" a good stand--field conditions can be too harsh for even the highest quality seed--it does greatly increase the probability that a good stand of vigorous plants will be established. On the other hand, seeds of low or poor physiological quality--although with an acceptable germination percentage--often
either fail to produce an acceptable stand or produce one that is less than satisfactory. A stand failure means additional costs for replanting and can mean loss of markets, and reduced yields. Less than satisfactory stands are often retained by farmers because of time and other constraints, even though they know that weed problems will be greater, produce quality will be poorer, and that there will probably be some short-fall in yield.

In terms of stand establishment, therefore, use of physiologically high quality seed is about the best "insurance" a farmer has against the adverse climatic conditions that often occur at or just after planting time (e.g., heavy rains, low soil temperatures).

**Plant Growth and Development**

There is no doubt that the reduced rates of germination and seedling growth associated with seeds of poor physiological quality "persist" during plant growth and development. Studies in our laboratory and elsewhere have shown that seedlings from poor quality seeds grow more slowly, develop less leaf area and flower somewhat later than those from seeds of high physiological quality. This reduction in rate of plant growth and development has been measured at both "normal" plant spacings and in individual plants isolated from competition from other plants. Slower plant growth and leaf area development delays the onset of the beneficial effects of shading and canopy closure in terms of weed control. In the case of root crops such as radish or turnips, slower growth means substantially less yield at harvest.

**Yield**

Yield studies conducted by our laboratory have indicated advantages for seed of high physiological quality. About half of studies have demonstrated reductions in yield of up to 10% attributable to poor physiological quality of the seed planted. It should be pointed out that in most of the studies referred to, reasonably good stands were produced for all treatments by adjusting plant rate on the basis of physiological quality of the seed. The other half of the studies indicated that while emergence and juvenile plant growth are reduced in plantings with seeds of poor physiological quality, the plants eventually "catch up" and yield is not reduced.

**Measurements of Physiological Seed Quality**

Reference has already been made to the increasing use of supplemental tests to evaluate the physiological quality or vigor of seed lots more accurately than is possible with the standard germination test. The supplemental tests used for this purpose are called "seed vigor tests."
The basic strategies followed in seed vigor testing are to establish the vigor level of a seed lot by direct measurement of the rate and/or status of some important seed property or process, or by evaluating the response/performance of seed lots under controlled conditions—usually "stress" conditions. These strategies are based on well-documented changes that occur in seed as they deteriorate.

Direct measurement of the rate/status of seed properties and processes include measurements of the "cellular energy status" or "ATP pool", the rate of respiration, the activity of specific enzyme systems, the "leakiness" of the seed membranes, and the rate of germination and seedling growth. Seed vigor evaluations based on the response or performance of seeds under controlled "stressful" conditions include the well known and widely used cold (soil) test for corn and other seed kinds, the cool temperature germination test for cotton seed, and the accelerated aging test for a variety of seed kinds. The four most widely used vigor tests are discussed below.

**Cold Soil Test**

The cold soil test was developed in the late 1930s to evaluate the germination and emergence capabilities of corn seed lots under laboratory conditions that stimulate the cold, wet field conditions that can occur at planting time. Corn seeds of the lots to be evaluated are planted in a mixture containing soil collected from a "cornfield" that is adjusted to a relatively high soil moisture level (fairly wet), and incubated at 50°F for 5 to 7 days. The tests are then moved to a warm temperature (80°F to 86°F) for emergence. Emergence of seeds of high vigor is only slightly reduced by the cold/wet soil stress, while emergence of low vigor seed is severely reduced. The cold test is also very useful for evaluating the efficacy of seed protectant fungicides applied to corn seeds. It also has been adapted for use for other kinds of seed, such as peas, soybeans, cotton. The correlation of cold test responses (emergence) and actual field emergence under cold and wet conditions is good.

**Accelerated Aging Test**

The accelerated aging (AA) test was originally developed to evaluate the storage potential of seed lots. However, since the storage potential of seed lots is a performance capability determined by the physiological quality or vigor of a seed lot, the AA test is also an excellent vigor test. Seeds of the lots to be tested are subjected to a high temperature (40 to 45°C or 104 to 113°F) at nearly 100% relative humidity for 3 to 6 days, depending on the kind of seed. At the end of the treatment, the seeds are planted for a standard germination test, and the germination percentage after AA is determined. The germination percentages of seed lots following accelerated aging are indicative of their vigor. High vigor seed lots retain their
Primary root growth is one expression of vigor.
germinability, while the germination of low vigor lots is severely reduced.

The AA test is used to evaluate vigor and storability of many kind of field, forage and vegetable crop seeds.

"Leakiness" or Conductivity Test

It has been well established that the permeability of seed membranes is impaired by deterioration - the seeds become "leaky" when placed in water. The leakiness of the seeds in a lot is determined by placing a specific number of seeds in a specific volume of deionized water for a period of time (usually 24 hours) and then measuring the electrical conductivity or resistance of the "steep" water with an electrode and resistance bridge. The materials that leak out of deteriorating seeds include electrolytes which decrease the resistance of water to the passage of an electric current. High vigor seed are not very leaky, so the water in which they are steeped gives a high resistance or low conductivity reading. Low vigor seed, on the other hand, can be very leaky and the steep water gives a low resistance or high conductivity reading. The conductivity tests are usually made on a seed sample, e.g., 20 to 100 seeds, but a modern instrument is available for evaluating conductivity on a individual seed basis.

The conductivity test is used in England for evaluating the vigor of pea and bean seed, and increasingly in the U.S. to evaluate seed vigor and storability in soybeans, beans and cotton.

Tetrazolium Test

The tetrazolium (TZ) test was developed in Germany in the early 1940s as a rapid method for estimating the germination of seed. Since the 1960s, the TZ test has gained wide acceptance not only as a rapid method for estimating germination, but also as a powerful method for assessing the vigor of seed and diagnosing physiological problems of seeds.

The TZ test is based on the reduction of a chemical (2,3,5-triphenyl tetrazolium chloride) from a soluble, colorless form to an insoluble red pigment by the activity of a group of enzymes in the cells of seed. The enzymes, dehydrogenases, are involved in respiratory processes in seed. Thus, their activity, i.e., capability to reduce TZ, is an index of the "aliveness" of seed cells and tissues. In the TZ test physiologically sound tissue stains bright red, physiologically weak tissue "stains" dark purplish red or faint red, and dead tissue does not stain. The physiological condition (or vigor) of individual seeds is evaluated by analysis of the extent and location of physiologically weak and dead tissue in the seed.
The overall objective of seed vigor testing is to evaluate the physiological quality of seed. The specific objectives in using any one or a battery of vigor tests ranges from diagnosis of physiological quality problems in in-house quality control programs to evaluating the stand and plant-producing potential of seed lots for marketing.

Summary

Crop stand establishment is mainly affected by the physiological quality or vigor of the seeds planted, the microenvironment of the seed bed, and their interactions. The germination test which has long been the standard test for evaluating the stand and plant producing potential of seed lots, has serious limitations. The test is made in the laboratory under near optimal conditions, which seldom occur in the field, and germinability, the seed capability evaluated, is lost only in the most advanced stages of deterioration. Recognition of the deficiencies of the germination test has prompted the development and increasing use of a variety of supplemental tests, called vigor tests, which can be used to establish the physiological quality or vigor of seed lots much more effectively than does the standard germination test.

The physiological quality of seed affects germination, emergence and plant growth and development. In certain situations, yield reductions can also be a consequence of planting seed of low physiological quality.

Considering the need of farmers to reduce the risks associated with crop production to the greatest extent possible, a decision to plant high quality seed is a good place to start.