

IRRADIATION OF FRESH MUSHROOMS

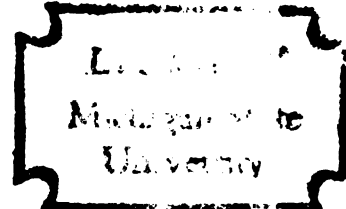
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ABSTRACT

IRRADIATION OF FRESH MUSHROOMS

by William Joseph Gill

Fresh cultured mushrooms (Agaricus bisporus) deteriorate quickly. Irradiation caused as much as a five-fold increase in storage life as measured by opening of the cap. The parameters Opening Ratio and Degree of Opening are defined herein and used, along with other physical measurements, to describe the effects of irradiation. Studies were made at temperatures in the range 3 to 15°C.

Although a dose of 10 Krads markedly reduced the rate of opening, higher doses gave some additional reduction. Moreover, a dose of 20 to 50 Krads was required to reduce shrinking of the stem. Stem elongation appeared to be retarded by 100 Krads, but doses of 10 and 20 Krads may have caused an increase in this rate. Irradiation (50 and 100 Krads) effectively retarded the rate of surface darkening. The rate of respiration was reduced by irradiation (10 to 100 Krads) when stored at 10 and 15°C, but not at 5°C. The texture was unchanged by doses below 200 Krads, but doses of 500 and 1,000 Krads caused a loss of 10 and 15 percent respectively. There was no clearly demonstrable change in the rate of transpiration as a result of irradiation. A delay between harvest and irradiation caused a slight reduction in the benefit derived from the irradiation treatment.

IRRADIATION OF FRESH MUSHROOMS

By

William Joseph Gill

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INTRODUCTION

The availability of fresh fruits and vegetables varies greatly from day to day and season to season. The majority of these commodities are quite perishable under usual marketing conditions. The value of fresh produce and the ease with which they are sold are greatly influenced by their quality when they are presented on the display shelves. While 84 standards have been established for 71 different fruits and vegetables (Dean, 1966), there have been no quality standards or methods of evaluation established for mushrooms.

Conditions to which fresh produce are exposed during storage or during display are usually quite variable, and are substantially different for different sections of the country or even from market to market. The U. S. D. A. has published recommended storage conditions for various fruits and vegetables (Wright, 1963), but these conditions are suggested, not required. The recommended storage temperature for mushrooms is 32°F with an optimum relative humidity of 85-90 percent.

Fresh fruits and vegetables are generally sold by weight, by the bunch, by the number, or in pre-weighed overwrapped trays. While awaiting sale, these commodities

are generally presented on cooled display shelves during which time their surfaces are exposed to warm air drafts, they are jostled and bruised by customers, and they may be exposed to airborne infection organisms.

According to Handbook No. 66 of the United States Department of Agriculture (Wright, 1966), fresh mushrooms will have prime quality for only 5 days at 32°F, 3 days at 40°F, or 1 day at 50°F. During storage, a number of deleterious changes occur in mushrooms. The change which causes the most concern and has the most striking effect on the appearance of the mushroom is the opening of the cap. As the mushroom caps open, the veils become stretched and finally break apart. Another major factor which promotes stretching of the veil is the decrease in the stem diameter which also occurs during storage. The increased distance between the edge of mushroom cap and the stem and the resulting separating of the veil combine to allow substantial exposure of the dark gills, giving the mushrooms an undesirable appearance. Other changes which occur during storage are elongation of the stems, surface and internal browning, and desiccation (especially of the outer surfaces).

Mushrooms are not considered an important source of carbohydrates, fats, protein, or vitamins. They are used primarily as a condiment--a seasoning used to add relish to food dishes. The composition of raw mushrooms, Agaricus bisporus, is given in Appendix B.

Investigations involving the use of irradiation as a means of food preservation have been performed by a number of researchers. Irradiation has been applied in three general dose ranges in an attempt to accomplish one of three objectives: Radiation doses in excess of 4.5 Mrad have been applied to ham, bacon, chicken, beef, and other meat and poultry products to accomplish commercial sterilization--that is, to destroy all microorganisms that might lead to spoilage of the product under normal storage conditions. Intermediate irradiation doses, in the range 100 to 2,000 Krads have been used as a means of pasteurization. That is, pasteurization in the sense that not all spoilage organisms and enzyme systems are destroyed in the product, but their numbers are reduced to such an extent that the shelf life after treatment is substantially extended. Pasteurization doses have been applied to luncheon meats, poultry, seafoods, and fruits and vegetables.

It has been found that low dose irradiation (5 to 500 Krads) retards certain physiological processes, especially in some fruits and vegetables. Early studies showed that very low doses, less than 20 Krads, had an inhibiting effect on the sprouting of potatoes and onions. Brownell (1957) found that at 5 Krads, sprouting is drastically retarded in potato tubers and completely inhibited by 20 Krads. Low doses have also been applied to onions to inhibit sprouting, to strawberries to reduce mold growth, and

to wheat and other grains as a method of disinfestation. Low dose irradiation has recently been applied to nearly all fruit and vegetable crops in an attempt to extend their fresh storage life.

Radiation is considered a food additive under the Federal Food, Drug, and Cosmetic Act of the United States Government (Additives amendment, 1958). Its use is regulated by the Food and Drug Administration and other government agencies. The regulations specify a minimum and maximum amount of particular kinds of ionizing radiation which may be used and the conditions for carrying out the radiation are specified. At present, the use of irradiation has been approved for only three foods. They are: 1) bacon, to which a sterilizing dose must be applied, 2) wheat and wheat products for the purpose of disinfestation, and 3) potatoes, as a sprouting inhibitor. Petitions for the approval of irradiation for other products have been, or soon will be, submitted to the Food and Drug Administration for approval. Ham and fresh strawberries are among the most promising products recently studied.

The Ministry of Health of the U.S.S.R. has approved still other products to be treated with ionizing radiation. In addition to potatoes and grain, official clearance has been given for the following products: dry fruits and dry food concentrates for disinfestation; fresh fruits and vegetables, raw meats, eviscerated chilled chicken, and

culinary prepared meat products for the reduction of micro-organisms for shelf life extension (radarization); and onions for the purpose of sprout inhibition (Metlitskii, 1967).

The earlier work with potatoes and onions suggested that the same or similar undesirable physiological processes which are retarded in these commodities might occur and be retarded in mushrooms. Several research groups have independently investigated the effects of irradiation on the physical characteristics of fresh cultured mushrooms.

Teply and Kline (1955) reported that mushrooms treated with doses from 0.1×10^6 to 6×10^6 rep showed no decrease in acceptability as measured by odor, although darkening increased with irradiation dose after irradiation in sealed polyethylene packages. The method of determination of the darkening and the effect of increased dose was not given. They also tested the activity of the mushroom tyrosinase and found that the activity was decreased by 21% at a dose of 10^5 rep and by 37% at 2.0×10^6 rep.

Staden (1964) presented irradiated and non-irradiated mushrooms to a taste panel and found, much to his surprise, that they indicated a definite preference for the flavor of the former. He also observed that the mushrooms, irradiated and subsequently stored, retained closed caps and remained light in color even after cooking.

Bramlage and Lipton (1965) found that radiation reduced post-harvest growth of mushrooms. Dose levels from 6.3 to 400 Krads inhibited opening of the cap with all doses being equally effective (5 Krad/minute, Co-60). They found this retardation at low as well as at high storage temperatures. In addition, they reported that 100 Krads significantly inhibited elongation of the stalks and that radiation inhibited expansion and darkening of the gills. Untreated samples and those given 6.3 and 12.5 Krad exhibited mold growth while no mold developed on those treated with 25 to 100 Krads. Recognizing the deleterious effects of desiccation on the appearance and quality of mushrooms, they stored samples in polyethylene bags to inhibit moisture loss. During this test, however, they found that none of the samples became dehydrated, whether packaged in polyethylene or not. (They apparently used visual observation to detect the degree of desiccation.) Bramlage and Lipton concluded, then, that although 100 Krads were necessary to inhibit significantly stalk elongation, mushrooms exposed to 50 Krads were just as attractive as those exposed to 100 Krads. Doses of 25 Krads or less were not as effective as 50 Krads in maintaining a fresh appearance.

Mercier and MacQueen (1965), generally verifying Staden's (1964) findings, found Agaricus campestris (recently renamed Agaricus Bisporus^a) reacted favorably to dose

^aR. Singer, Lilloa, Vol. 22, p. 431, 1949.

levels of gamma irradiation from Co-60 between 100 and 300 Krads. They observed that between 0 and 300 Krads an increase in dose produced a corresponding reduction in cap opening even one day after irradiation. After six days of storage at room temperature, the caps treated at 50 Krads and higher doses had enlarged only slightly; noticeable retardation of stem elongation required a higher dose (about 100 Krads). Mushrooms irradiated with 100 Krads or more retained normal skin color for at least 10 days at room temperature. Skin color was apparently evaluated subjectively. Unirradiated lots received poor color ratings after the third day of holding. At that time, the mushrooms had started to shrivel, were discolored, and were 2.5 to 5% lighter than the irradiated lots (unspecified method of measurement). Flavor and texture evaluations by ten families indicated that irradiated mushrooms can stay fresh much longer than unirradiated ones. Mercier and MacQueen recommend 200 Krads as an optimum irradiation dose to give maximum quality retention. Their study of respiration rate revealed that soon after irradiation, the rate of CO_2 evolution increased. (The measurements were made with an infra-red CO_2 analyzer, but the type of system, opened or closed, was not specified.) The rate of evolution for control samples was about 200 grams of CO_2 per gram of mushrooms in one hour (this amount is equivalent to about 10.2 ml CO_2 /100 g-hour) when held at room temperature at 4 hours

after treatment. However, one day after irradiation, the controls showed the highest activity. This finding led them to postulate that gamma rays extend the shelf-life of mushrooms by inhibiting some of the enzyme systems involved in postharvest deterioration. This postulation is questionable, however, since most enzyme systems studied are not substantially effected by doses less than 2 to 4 Mrads (Siu, 1958; Brownell, 1961).

Research by Langerak and Van Kooy (1965) revealed that packaging mushrooms in foodtainers sealed with foil gave extended shelf lives whether or not irradiation has been applied. They found the permeability of the plastic foils to be very important; that is, the respiration of the packed product should not be hindered by oxygen depletion or CO₂ accumulation while the permeability of the foil should be such that too much desiccation of the product is prevented.

As early as 1963, experiments by Staden indicated an inhibition of the rate of cap opening by irradiation. Later investigations (Staden, 1966) showed irradiation to have other effects on the quality of mushrooms. He advised that doses in excess of 350 Krads may increase brown discoloration, and recommended 100 Krads as an adequate dose provided there was good penetration. His studies indicate a direct relationship between effectiveness and degree of penetration of the electrons or rays. From this, it follows

that 3 Mev electrons will give better results than 1 Mev and that 3 Mev has a slightly poorer effect than X-rays even if the mushrooms are spread out in one layer. As one might expect, it was found that the most significant retardation in cap opening and the longest extension of the shelf life was obtained when the time between harvesting and irradiation was kept at a minimum. A delay of one day greatly reduced the effectiveness of the irradiation treatment. Staden found irradiated mushrooms retained their white color during storage and displayed less elongation of the stalk. His studies suggest that the irradiation treatment may also retard the development of mold on the surfaces of the mushrooms. In addition, flavor evaluations of test mushrooms indicated a slight preference for those that were irradiated. This result led him to conclude that irradiation also preserves taste and flavor.

Successful use of gamma irradiation to retard cap opening of Agaricus bisporus at Michigan State University (1966) prompted Maxie and his co-workers (Maxie, 1967) to investigate this phenomenon in a brown cultured mushroom. Medium sized brown mushrooms, irradiated and non-irradiated, were packed in brown paper bags containing moist paper towels, and stored at 32, 41, and 68°F. Maxie and his associates reported little or no advantage with irradiation when the mushrooms were stored at 32°F. However, irradiation did reduce the rate of cap opening of mushrooms stored

at 41 and 68°F, and the differences, relative to dose, were not great at either temperature. The irradiated samples were considerably better than were the controls. Their research showed ". . . no real advantage in the use of irradiation at any dose [0 to 100 Krads] and temperature on the rate of stem growth."

Sensory evaluations conducted by Maxie showed no difference between 0 and 100 Krads on closed mushrooms, but there was a highly significant ($P = 0.001$) difference in the flavor of raw, slightly opened mushrooms treated with 0 and 100 Krads. No difference was detected in the aroma, however. Visual observation revealed that the irradiated mushrooms tended to dry out and become porous at the end of this storage period. These texture differences (shriveling and porosity), according to Maxie, undoubtedly influenced the judges' ability to differentiate between the control and irradiated samples.

Maxie's investigations also showed no effect of irradiation on the ascorbic acid content of mushrooms as measured by the method of Loeffler and Ponting (1942, Ind. Eng. Chem. Anal. Ed. 14:846-849) for reduced ascorbic acid or by the method of Hughes (1956, Biochem. J. 64:203-208) for measuring total ascorbic acid.

Lipton, Harvey, and Couey (1967) reported a reduction in the elongation of stems, reduced expansion and darkening of the gills, and inhibition of surface-growing

molds when mushrooms were exposed to radiation. These effects were found to be most pronounced when the mushrooms were treated with 100 Krads, but a 50 Krad dose was almost as effective. The effects of irradiation were found to be about the same whether the mushrooms were held 2 or 4 days at 32°F plus 2 or 4 days at 70°F, or 3 days at 41°F plus 3, 5, or 7 days at 50°F.

Researchers, then, have studied the effects of irradiation on several quality factors of mushrooms. They generally agree that irradiation retards opening of the cap, but there is disagreement among them as to the effect of irradiation on other quality factors and as to the optimum radiation dose. While Mercier and MacQueen (1965) suggest that 200 Krads are necessary for maximum quality retention, Lipton et al. (1967) found 100 Krads to have the most pronounced effect with 50 Krads being almost as effective. The effect of irradiation on the browning rate of mushrooms is unresolved, and, again, an objective and accurate method of measuring the degree of browning is desirable. No researcher cites any method of color evaluation other than personal impression.

Researchers are in disagreement as to the effect of irradiation on the elongation of the stem. Bramlage and Lipton (1965) and Maxie et al. (1967) studied the effect of irradiation in the range 0 to 100 Krads on the rate of stem elongation. While Maxie found no advantage at any

dose or any storage temperature (32, 41, or 48°F), Bramlage and Lipton reported a definite reduction in the stem elongation at the higher doses in this range. The reason for this discrepancy is not clear, but differences in source dosimetry or the degree of desiccation during storage may be responsible. Also, there has been no satisfactory method of evaluating the opening of the cap presented or described by these researchers. Bramlage and Lipton (1965) and Mercier and MacQueen (1965) reported opening values based on the extent of opening, but did not use clearly defined scales on which objective measurements could be made. The scales they used consisted of, ". . . opening was rated on a scale: 1 = tightly closed; 3 = puffy but closed; 5 = slightly open; . . ." (Bramlage and Lipton) and, "0 was completely opened, 3 and 5--closed." (Mercier and MacQueen). These scales were obviously subjective and could not be satisfactorily used by other workers attempting to reproduce or to compare their results. Maxie et al. (1967) used the increase in the cap diameter as a means of following opening. This method, although reproducible and objective, does not take into account other factors, such as shrinking of the stem, which also affect the apparent opening. Other workers have not even attempted to define their methods of evaluating openness of cap. In addition, other factors which influence quality such as transpiration rate, respiration rate, and texture and how these factors

are affected by irradiation have not been investigated adequately.

The purpose of this study was to investigate the effects of low dose gamma irradiation from Co-60 on the quality of fresh cultured mushrooms, Agaricus bisporus, by the use of measurements that are clearly defined, that are truly representative of the phenomenon under investigation, that lend themselves to statistical analysis, and that can be readily used by other workers.

METHODS AND MATERIALS

Mushrooms

The mushrooms used in these experiments were a white strain of Agaricus bisporus. Fresh cultured mushrooms of this variety were obtained through the courtesy of the Great Lakes Mushroom Co-operative, Warren, Michigan. The mushrooms were harvested fresh on the day they were to be treated and held at 35°F until they were transported to the irradiation facility. The distances traveled were: Warren to Ann Arbor about 60 miles, Warren to East Lansing about 110 miles, and Ann Arbor to East Lansing about 70 miles.

Methods of irradiation

After July 1, 1967, irradiations were performed at the 51,000 Curie Michigan State University Food Science gamma facility. Prior to this time, irradiation treatments were administered with the 9,000 Curie irradiator housed in the Phoenix Memorial Laboratory, University of Michigan, Ann Arbor. In all cases, containers filled with mushrooms were placed at measured distances from the source center and exposed to gamma-radiation for a pre-determined length

of time (Appendix A). The times and distances were based on doses previously measured by chemical dosimetry (Appendix A).

Containers

Irradiated and non-irradiated samples were treated and stored in containers differing in size, shape, permeability, construction material, and in the extent to which they allowed ventilation. Descriptions of the containers used in the course of the investigations are listed below.

1. One pint wooden basket with no over-wrap.
2. One pint wooden basket wrapped and sealed with an unperforated 1-1/2 mil. polyethylene film.
3. One pint wooden basket over-wrapped with a perforated 1-1/2 mil. polyethylene film.
4. One quart polyethylene cottage cheese tub with no cover.
5. One quart polyethylene cottage cheese tub covered with an unperforated polyethylene film.
6. One quart polyethylene cottage cheese tub covered with a polyethylene film having four 1/4 in. perforations.
7. One quart polyethylene cottage cheese tub covered with unperforated film, but provided with six 3/8 in. perforations, 3 at 1-1/2 in. from top and 3 at 1-1/2 in. from bottom.

8. A commercial one-pound mushroom box, provided with an internal wax coating, and having ten $7/16$ in. perforations, 4 on top and bottom and one at each end.
9. A commercial mushroom box as in (8), but with the perforations reduced to $1/4$ in.
10. A chipboard egg filler flat, capacity 2- $1/2$ dozen, over-wrapped, but not sealed, with an unperforated polyethylene bag.

Quality evaluation

Color: The reflectance, L_D , was used as a means of describing the degree of browning in mushrooms. The L_D was measured on a scale from 0 (black) to 100 (white) with a Gardner Color Difference Meter. Individual mushrooms were placed cap down into the diaphragm, therefore allowing them to protrude more or less into the opening depending on the diameter and shape of the cap. Also, the diaphragm had such a diameter that only large mushrooms could be measured, medium and small sized ones had diameters smaller than that of the diaphragm. These difficulties made the measurements doubtful in precision and accuracy.

Texture: The texture, as measured by peak shear resistance, of treated and untreated mushrooms was measured with an Allo-Kramer shear press. Seventy-five gram subsamples of master samples were tested with a multiple blade

shear cell. The shear press was adapted to the appropriate range for mushroom measurements by the use of a 250 lb. pressure ring with the range setting on 50 and the selector at the low position. These conditions provided a measurement range of 0 to 100 microamperes.

Respiration: Several methods have been, and are currently being employed to determine the rate of respiration of various "living" commodities. Many are based on measurements of oxygen consumption or carbon dioxide evolution in either an open (gas flow) or closed (hermetically sealed) system. The open system has an important advantage in avoiding excessive depletion of oxygen or accumulation of carbon dioxide or other metabolically active volatile gases. The gas accumulation or depletion can have a tremendous effect on the rate of respiration. Also, open systems are readily adapted to analysis by automatic, continuous systems. The rate of respiration of treated and untreated mushrooms was measured by the method and with the equipment described by Dilley (1966). The oxygen consumption and carbon dioxide evolution in an open system was monitored over a 4-1/2 day period. The instruments used to make these gas exchange measurements were a Beckman IR-115 Infrared Carbon Dioxide Analyzer and a Beckman Model G-2 Oxygen Analyzer.

Transpiration: Transpiration rates, water loss through evaporation during storage, were calculated from

weight loss measurements. Treated and untreated mushrooms stored in containers of various styles were weighed at a number of times during the storage period. The weights of containers filled with mushrooms (250-300 grams) or individual mushrooms (5-18 grams) were measured to the nearest 0.1 gram with a top loading Mettler P-1200 balance.

Storage facilities: Three different refrigerated storages were used in testing the effects of storage. The first facility consisted of three walk-in rooms with the temperature controlled to $\pm 0.5^{\circ}\text{C}$, held at 5, 10, and 15°C . These were the rooms in which the samples were held during the respiration studies. The second was wooden ripening boxes provided with heaters to raise the temperature above ambient and fans to keep the air circulated. The temperature could be controlled to $\pm 0.5^{\circ}\text{F}$. The relative humidity was about 70 percent with an air flow of approximately 36 feet/minute. The third facility was stainless steel cubicles with a temperature control of $\pm 1^{\circ}\text{F}$. These cubicles were provided with fans which gave rapid air flow over the containers.

Opening: Since the opening of the cap is the change which has the greatest influence on the degradation of the appearance of mushrooms, an accurate and precise means of measuring and following this change throughout the storage period seemed essential. Freshly harvested mushrooms usually have tightly closed caps. During storage, however, the cap

(pileus) begins to expand, the gill (lamellae) tips move farther and farther away from the stem (stipe), the veil (velum) breaks apart exposing the gills, and the cap continues to open, increasing the exposure of the dark gills (See Fig. I). During this progression, the mushrooms take on a puffy appearance followed by splitting of the veil. Therefore, a rapid and simple method of describing the extent of veil separation was devised and was called the Degree of Opening, D.O. The D.O. is a physical measurement of the portion of the circumference in which the veil has separated from the cap and ring (annulus). This measurement was made with a radial scalor provided with ten 36 degree divisions labelled 0.0 to 0.9. Placing the radial scalor over the underside of a mushroom allowed measurement of the D.O. from 0.0 to 1.0. This method of measurement was found to be simple and rapid, but it was not useful in describing the progression of opening before the veil begins to separate or after it has completely separated. Also, it was found that the veil did not always separate at the same given stage of cap opening. If the relative humidity was such as to allow excessive desiccation of the veil, it would become less elastic and separate at an earlier stage in the progress of opening.

A method of measuring the opening of the cap independent of the separation of the veil was needed in order to describe accurately the extent of cap opening before or



Fig. 1. Mushrooms showing the progression of cap opening during storage.

after this separation had occurred. Slicing a mushroom down the center laterally exposes the internal structure in such a way that meaningful measurements could be made. It was found that distances between certain points on this internal surface changed as mushrooms opened. Figure II shows internal sections of mushrooms at various stages of opening. As opening progresses, the gill tips move farther from the edge of the stem. The observation of this phenomenon suggested that a ratio could be set up to describe the opening that would not be appreciably influenced by mushroom size or by factors such as desiccation which influenced separation of the veil. Figure III is a sketch of the described internal surface of a mushroom showing five measurements that were made with a dial caliper capable of being read to the nearest 0.0005 inch. These measurements were then used to set up and calculate the Opening Ratio; $\frac{b + c}{a - (b + c)}$ or, $\frac{e - d}{a - (e - d)}$. These ratios are, of course, equal by definition so that only three measurements were necessary to arrive at an O.R. The "a" value is the overall cap diameter at the time of measurement, the quantity (b + c) or (e - d) is the total opening gap, and a - (b + c) or a - (e - d) is an "effective" diameter--that is, the cap diameter adjusted for the separation between the gill tips and the stem. The above ratios, then, would represent the ratio of the total opening gap to the "effective" closed cap diameter. Therefore, as cap opening continues, the O.R. also increases.

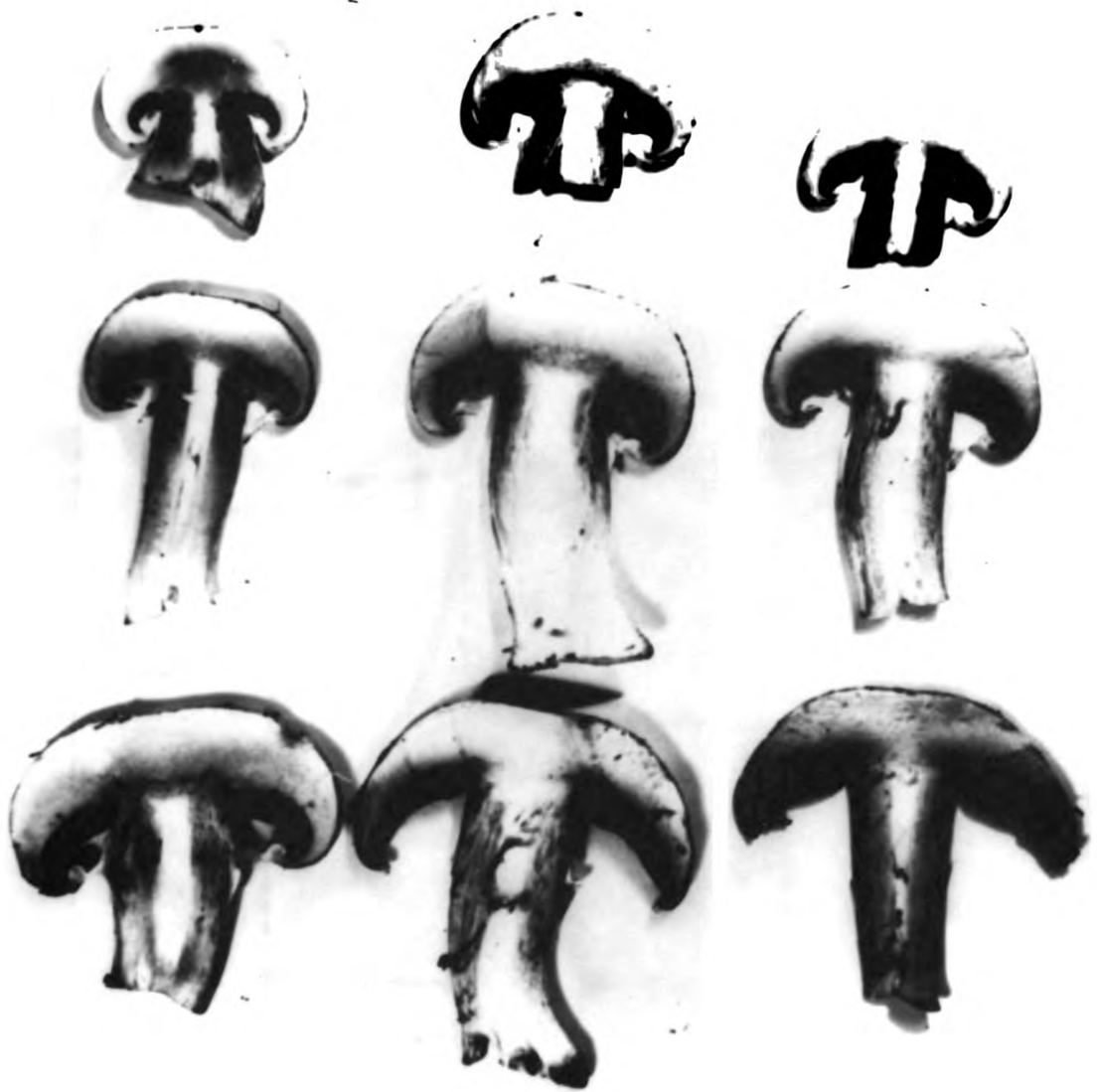


Fig. II. Internal sections of mushrooms at various stages in the progression of cap opening.

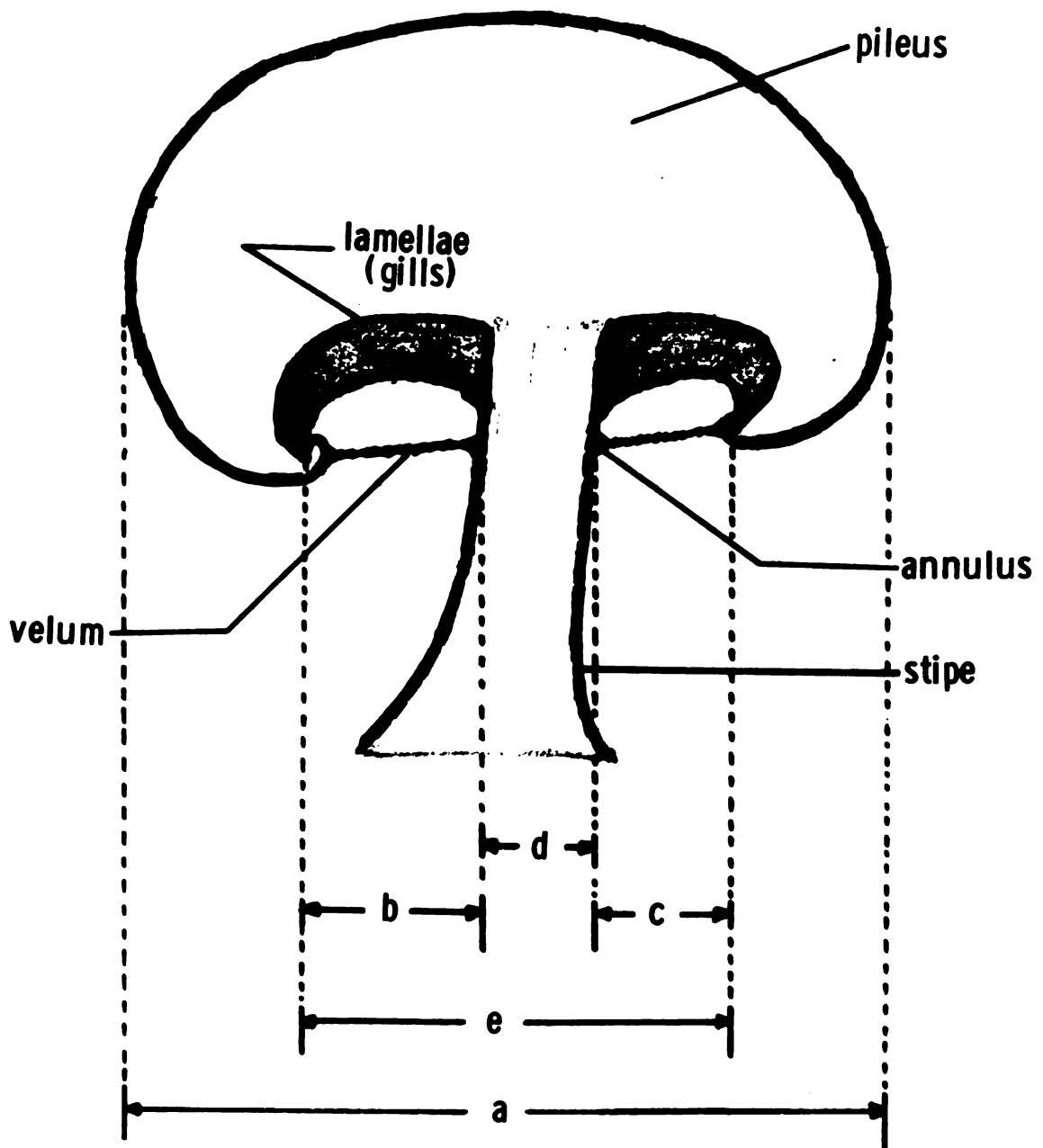


Fig. III. Cross section of a mushroom showing the dimensions that were measured.

It was found that a very tightly closed mushroom has an O.R. of about 0.15 (the gill tips never actually touch the stem) and an extremely opened mushroom was found to have an O.R. of about 4.0. This method was found to be quite time consuming and tedious, but yielded data that were reliable and could be used to describe the extent of opening at any time during the cap opening progression. Also, values obtained from different lots of mushrooms could be compared without regard to factors such as relative humidity of storage which would limit the use of D.O. An equal O.R., then, becomes the criterion of an equal extent of opening, and, therefore, equal quality as based on the most critical change in appearance which occurs during storage, the opening of the cap.

Elongation of the stem: Lengthening of the stem was determined by measurements of the total mushroom height. The distance from the upper most part of the cap to the bottom edge of the stem was made with the dial caliper previously described. It must be remembered that the mushroom height also includes the thickness of the mushroom cap. If it is assumed that the mushroom cap does not change appreciably in thickness, then any change in the height is primarily a result of stem elongation. Nevertheless, since the elongation is usually expressed as percent, the inclusion of the cap in the measurement results in an apparent percent change in the stipe length that is somewhat less than the change

that actually occurs. The cap may account for 20 to 30 percent of the mushroom height.

EXPERIMENTAL AND RESULTS

Dimensional changes

The importance of the opening of the cap on the appearance of mushrooms prompted studies of the effects of irradiation dose, storage time, storage temperature, delay between harvest and irradiation, storage atmosphere on cap opening and other dimensional changes.

Experiment I: Opening versus irradiation dose and storage time.

Fresh mushrooms were transported from Warren to Ann Arbor (about 60 miles) where they were sorted--only tightly closed mushrooms of uniform quality were used--and placed into one-pint wooden baskets. They were then given doses of 0, 10, 15, 20, and 50 Krads (dose rates from 6.7 to 33.3 Krads/hour), and transported to East Lansing where they were stored at 3.3°C.

At the end of 2, 7, 15, and 21 days, two pints of each treatment were removed from storage and tested for the Degree of Opening (D.O.) and the Opening Ratio (O.R.). Table 1 gives the D.O. and O.R. values for the mushrooms at the four storage intervals.

Table 1. Opening Ratio and Degree of Opening of irradiated mushrooms. Average of 25 to 30 mushrooms stored at 3.3°C.

Dose Krad	Storage time, days							
	2		7		15		21	
	O.R.	D.O.	O.R.	D.O. ^b	O.R.	D.O.	O.R.	D.O.
0	0.35	0.00	0.39	--	0.68	0.30	0.78	0.42
10	0.31	0.00	0.44	--	0.44	0.01	0.50	0.02
15	0.28	0.00	0.41	--	0.54	0.01	0.44	0.02
20	0.40	0.00	0.38	--	0.49	0.01	0.47	0.00
50 ^a	0.34	0.00	0.42	--	0.53	0.01	0.54	0.00

^aThe 50 Krad samples seemed to be somewhat more desiccated than the others.

^bDegree of Opening measurements were not taken at 7 days.

The effect of the gamma irradiation treatment did not become evident until the mushrooms had been stored for 15 days at 3.3°C. By this time, the control samples had an average O.R. of 0.68 and an average D.O. of 0.30. The combined (all doses except 0 Krad) irradiated samples, however, had an average O.R. of 0.50 and an average D.O. of 0.01. At 21 days storage, the effect is even more evident. The control samples had an O.R. and D.O. of 0.78 and 0.42 respectively, compared to 0.49 and 0.01 for the combined irradiated treatments.

Experiment II: The effect of dose and storage temperature.

Freshly harvested mushrooms were obtained in Warren and transported to Ann Arbor where they were sorted--only mushrooms of medium size and tightly closed veils were used--and placed in wooden pint baskets. Doses of 0, 10, 20, 50, and 100 Krads were each given to 15 baskets in a period of one hour. All samples were then transported to East Lansing where they were placed in ventilated polyethylene pails and stored in three temperature controlled rooms at 5, 10, and 15°C, after overnight storage at 3.3°C.

Seven days after irradiation, 20 mushrooms of each treatment were measured for O.R. and D.O. Table 2 gives the average values of these measurements. The average "a" (overall cap diameter) values are also included. Irradiation, even at a dose of 10 Krads, greatly reduced the rate of cap opening. This reduction was especially noticeable when the mushrooms were stored at the higher temperatures (10 and 15°C). The control (0 Krad) samples stored at 15°C had an O.R. of 2.49 while the samples given 10, 20, 50, and 100 Krads of gamma irradiation had O.R.'s of 0.67, 0.76, 0.79, and 0.57 respectively. A similar reduction was observed in the D.O. values. In addition, even when the samples were stored at the lowest temperature, 5°C, the D.O. values for 0, 10, 20, 50, and 100 Krad doses were 0.57, 0.06, 0.06, 0.02, and 0.01, respectively.

Table 2. Opening Ratio, Degree of Opening, and cap diameter (inches) of irradiated mushrooms held at 5, 10, and 15°C for seven days.^a Average of 20 mushrooms per temperature and gamma ray dose.

Storage Temp.	Dose Krad	Cap Diameter a	O.R.	D.O.
5°C	0	1.59	0.76	0.57
	10	1.49	0.68	0.06
	20	1.52	0.54	0.06
	50	1.51	0.56	0.02
	100	1.55	0.51	0.01
10°C	0	1.74	1.21	0.98
	10	1.49	0.70	0.83
	20	1.46	0.64	0.67
	50	1.55	0.63	0.32
	100	1.49	0.59	0.11
15°C	0	1.90	2.49	1.00
	10	1.53	0.67	0.90
	20	1.48	0.76	0.86
	50	1.58	0.79	0.69
	100	1.52	0.57	0.11

^aStored at 5, 10, and 15°C after overnight storage at 3.3°C.

There was also a significant difference in the cap diameter between irradiated and non-irradiated samples. This difference was greater at higher temperatures but evident even at 5°C. The control (0 Krad) samples had cap diameters of 0.59, 1.74, and 1.90 inches compared to 1.52, 1.50, and 1.53 inches for the combined irradiated samples for 5, 10, and 15°C, respectively. There was no significant difference among irradiation doses at any temperature.

Experiment IV: The effects of dose and container style on dimensional changes.

The effects of storage atmosphere and irradiation dose were studied by storing irradiated and non-irradiated mushrooms in containers of different styles which differed primarily in their ability to permit ventilation. Fresh mushrooms were obtained in Warren and transported directly to East Lansing. Medium sized (about 1.3-inch diameter) mushrooms with tightly closed caps were randomly placed into five different styles of containers.

- 1) One quart polyethylene tub with no cover,
- 2) One quart polyethylene tub, open end covered with an unperforated polyethylene film,
- 3) One quart polyethylene tub with six 3/8-inch diameter perforations (three at 1-1/2 inches from top and three at 1-1/2 inches from bottom) and covered with unperforated polyethylene film,

- 4) Commercial one pound mushroom box having an internal wax coating and ten 7/16-inch diameter perforations (four on top and bottom and one on each of two sides),
- 5) Modified commercial box--same as in (4) but with perforations reduced to 1/4-inch diameter.

Doses of 0, 10, and 100 Krads were each given to two filled containers of each style (30 containers total) on the following morning in Ann Arbor. On return to East Lansing, the mushrooms were stored at 10°C.

The D.O. of these mushrooms was measured after seven days of storage. The results of these measurements are given in Table 3. Again, irradiation had a significant effect on the rate of cap opening as measured by D.O. in all cases, the 100 Krad samples opened less than did the control samples. The 10 Krad samples also opened less than did the controls in all packages except the commercial box where both were at D.O. = 1.00.

Table 3. Degree of Opening of mushrooms stored at 50°C for 7 days. Average of 25 to 40 mushrooms per treatment.

Container Style	Dose, Krad		
	0	10	100
Open Tub (1)	1.00	0.50	0.10
Sealed Tub (2)	0.50	0.30	0.34
Perforated Tub (3)	1.00	0.66	0.54
Commercial Box (4)	1.00	1.00	0.36
Modified Comm. Box (5)	1.00	0.95	0.47

The data also show that the type of container in which the mushrooms were stored affected the rate of cap opening. Mushrooms stored in sealed containers (style 2) proved to be considerably less opened than those stored in other containers. The control (0 Krad) samples stored in this container had a D.O. of only 0.50 as compared to 1.00 for all other unirradiated samples. The containers allowed more or less opening of the 10 and 100 Krad samples depending on how well they were ventilated. Increasing the ventilation allowed greater opening of the caps and thus a more substantial difference between doses of 10 and 100 Krads with 100 Krads showing the greater effectiveness.

Experiment V: The effect of irradiation dose.

Freshly harvested mushrooms were again obtained in Warren and transported to East Lansing where they were sorted in a cold room (10°C); only tightly closed mushrooms of good quality and medium size were used. The mushrooms were packed into 60 one-quart polyethylene tubs having six 3/8-inch diameter perforations in the side and covered with an unperforated polyethylene film. Doses of 0, 10, 20, 50, and 100 Krads were each applied to 12 tubs with the M.S.U. Food Science gamma facility. Following irradiation, the samples were stored at 10°C.

Five hours after irradiation, 60 non-irradiated mushrooms were measured for the Degree of Opening and the Opening Ratio. The D.O. at this time was 0.0 and the average

O.R. was 0.28. Thirty mushrooms of each treatment were measured for the O.R. and D.O. at 1.2, 2.2, 4.2, and 7.2 days after irradiation (stored at 10°C). The average values calculated from these measurements are reported in Table 4.

Table 4. Opening Ratio and Degree of Opening of mushrooms stored in perforated tubs at 10°C. Average of measurements on 30 mushrooms for each dose and time interval.

Dose Krad	Storage time after irradiation, days							
	1.2		2.2		4.2		7.2	
	O.R.	D.O.	O.R.	D.O.	O.R.	D.O.	O.R.	D.O.
0	0.40	0.22	0.48	0.43	0.71	0.91	1.30	0.99
10	0.36	0.12	0.34	0.11	0.42	0.51	0.53	0.79
20	0.32	0.02	0.40	0.33	0.49	0.55	0.47	0.52
50	0.27	0.00	0.30	0.15	0.41	0.21	0.53	0.56
100	0.36	0.02	0.37	0.02	0.48	0.35	0.53	0.36

At each testing time, the control samples (0 Krad) had higher O.R. and D.O. values than did any of the irradiated samples. After 1.2 days of storage, the 0 Krad samples had about the same O.R. and D.O. as the 50 Krad samples after 4.2 days. At the end of 7.2 days storage at 10°C, the 20, 50, and 100 Krad treatments had an acceptable appearance. Some of the veils had begun to break apart, but this effect was due largely to desiccation during

storage. The control samples had extremely opened caps and seemed to be somewhat darker in color than the irradiated samples, especially those given 50 and 100 Krads of gamma irradiation.

Experiment VI: The effect of irradiation dose on the cap diameter, stipe diameter, height, and D.O.

On November 30, 1967, fresh mushrooms were transported from Warren to East Lansing where all defective and opened mushrooms were sorted out leaving only tightly closed mushrooms of uniform size. These mushrooms were placed in perforated polyethylene tubs and given doses of 0, 10, 20, 50, and 100 Krads. Fifteen mushrooms of each dose were then placed stem up in chipboard egg filler flats (two doses per flat), covered with unperforated polyethylene, and stored at 10°C. Measurements of cap diameter, stem diameter just below the ring, and the Degree of Opening were made on each mushroom at 0, 2.0, 4.1, 7.0, and 11.0 days after irradiation. Table 5 gives the average (15 mushrooms) percent changes in the physical dimensions.

The cap diameter was found to increase linearly with time for the control (0 Krad) samples. This increase, however, was markedly reduced by irradiation in the dose range 10 to 100 Krads (10, 20, 50, and 100 Krads). Doses of 50 and 100 Krads seemed to have more of an effect than 10 and 20 Krads, but not in proportion to additional dose.

Table 5. Percent changes in cap diameter, stem diameter, and height, and average Degree of Opening of mushrooms stored at 10°C. Average of the same 15 mushrooms throughout the storage period.

Dose Krad	Days storage	Cap. dia. % increase	Stipe dia. % increase	Height % increase	Ave. D.O.
0	2.0	2.9	7.4	3.5	0.00
	4.1	7.9	18.8	16.3	0.95
	7.0	16.4	27.2	31.8	1.00
	11.0	25.2	31.2	35.5	1.00
10	2.0	2.6	3.7	5.8	0.00
	4.1	3.2	11.4	21.4	0.28
	7.0	5.7	21.1	39.6	0.76
	11.0	7.1	26.7	42.7	0.80
20	2.0	4.4	5.6	7.5	0.00
	4.1	5.2	11.8	31.7	0.53
	7.0	7.4	16.6	47.4	0.72
	11.0	7.8	22.6	49.4	0.83
50	2.0	3.4	4.8	6.7	0.00
	4.1	4.9	12.4	23.2	0.18
	7.0	5.3	15.0	34.0	0.38
	11.0	4.7	20.6	35.5	0.45
100	2.0	1.5	5.1	4.1	0.00
	4.1	3.0	12.5	11.5	0.00
	7.0	3.5	16.2	9.7	0.00
	11.0	2.5	21.3	18.7	0.03

The stem diameter of all treatments decreased linearly with time. This decrease was significantly greater at doses of 0 and 10 Krads than at 20, 50, and 100 Krads. The height of the mushrooms, a measurement used to follow stem lengthening, increased with time at all doses, but the rate of increase became less after 6 to 7 days at 10°C. A dose of 100 Krads retarded the rate of increase, but a 20 Krad dose accelerated this increase above the rate of the control (0 Krad) mushrooms. About the same rate of increase was observed for doses of 0, 10, and 50 Krads.

As has been shown by past experiments, the Degree of Opening (D.O.) was greatly affected by irradiation dose. The control samples were more open at two days than any of the irradiated samples were after 11 days at 10°C. Mushrooms treated with 100 Krads opened least (D.O. = 0.03 after 11 days) with the 50 Krad samples (D.O. = 0.45 at 11 days) opening less than the 10 and 20 Krad samples (D.O. = 0.80 and 0.83 at 11 days.)

Experiment VII: The effect of dose and storage temperature.

On December 18, 1967, fresh mushrooms were transported from Warren to East Lansing. They were carefully sorted to eliminate opened, bruised, or irregularly shaped mushrooms and to produce more uniformity within the samples. The mushrooms were placed in one-quart polyethylene tubs and doses of 0, 50, 100, and 200 Krads were applied at the

M.S.U. Food Science gamma facility. Following irradiation, they were placed on numbered chipboard egg filler flats (two doses per flat, 15 mushrooms per treatment) as in Experiment VI. The flats were covered with unperforated polyethylene and stored at 5, 10, and 15°C in temperature controlled cubicles. An initial measurement of O.R. was made at 0.0 time on 20 mushrooms.

Mushrooms stored at 15°C were measured for a (cap diameter) and D.O. at 0.0, 1.0, 2.0, 3.0, and 4.0 days after irradiation and O.R. was measured at the end of the 4 day period. Those stored at 10°C were measured for a and D.O. at 0.0, 2.0, 4.0, 8.0, 11.0, and 15.0 days after irradiation and O.R. measurements made at the end of the 15 day interval. The mushrooms stored at 5°C were measured for a and D.O. at 0.0, 4.0, 8.0, 15.0, and 21 days. The results are reported in Tables 6, 7 and 8.

Conclusions regarding the effects of irradiation dose and storage temperature on the increase in cap diameter can be made from Table 6. The Q_{10} for a of the control (0 Krad) samples was calculated to be 6.7 at 4 days of storage. The increase in the cap diameter was greater with increased storage temperature at all dose levels, but the temperature effect was not as great in irradiated samples (Q_{10} about 3). The cap diameters of the control samples increased more than any of the irradiated samples at each storage temperature and all testing times. By the end

Table 6. Percent increase in cap diameter, a , of irradiated mushrooms stored at 5, 10, and 15°C in egg filler flats. Average of 15 mushrooms.

Dose Krad	Storage Temp., °C	Storage time, days							
		1.0	2.0	3.0	4.0	8.0	11.0	15.0	21.0
0	5	---	---	---	3.9	5.6	---	8.4	9.5
	10	---	4.2	---	9.1	18.0	21.0	24.0	---
	15	5.0	14.0	22.0	26.0	---	---	---	---
50	5	---	---	---	2.1	4.6	---	5.1	4.7
	10	---	2.9	---	5.0	6.5	5.9	5.0	---
	15	1.8	3.8	5.4	5.9	---	---	---	---
100	5	---	---	---	2.2	4.6	---	4.7	4.6
	10	---	3.2	---	5.9	7.0	6.6	5.1	---
	15	2.2	4.7	6.0	6.6	---	---	---	---
200	5	---	---	---	1.9	3.9	---	3.4	2.8
	10	---	1.9	---	4.9	6.4	6.1	3.6	---
	15	1.4	4.2	5.0	5.2	---	---	---	---

Table 7. Degree of Opening of irradiated mushrooms stored at 5, 10, and 15°C in egg filler flats. Average of 15 mushrooms.

Dose Krad	Storage Temp., °C	Storage time, days							
		1.0	2.0	3.0	4.0	8.0	11.0	15.0	21.0
0	5	---	---	---	.05	.26	---	.43	.57
	10	---	.13	---	.30	.67	.79	.85	---
	15	.19	.46	.93	1.00	---	---	---	---
50	5	---	---	---	.00	.09	---	.18	.19
	10	---	.00	---	.09	.27	.29	.29	---
	15	.00	.04	.29	.47	---	---	---	---
100	5	---	---	---	.00	.03	---	.12	.15
	10	---	.00	---	.00	.05	.06	.05	---
	15	.00	.11	.13	.19	---	---	---	---
200	5	---	---	---	.01	.06	---	.09	.11
	10	---	.00	---	.00	.00	.02	.02	---
	15	.00	.05	.05	.13	.15	---	---	---

Table 8. Opening Ratio and O.R./day of irradiated mushrooms stored at 5, 10, and 15°C in egg filler flats. Average of 15 mushrooms.

Dose Krad	O.R. at 0 days	15°C for 4 days		10°C for 15 days		5°C for 21 days	
		O.R.	O.R./day	O.R.	O.R./day	O.R.	O.R./day
0	.35	1.21	.22	1.94	.11	1.02	.032
50	.35	.56	.052	.58	.015	.56	.010
100	.35	.52	.042	.42	.0047	.60	.012
200	.35	.48	.032	.42	.0047	.49	.0067

of the storage times, the cap diameters of the 0 Krad samples had, in general, increased 4 to 5 times as much as those of the irradiated samples. Doses of 50 and 100 Krads retarded the increase in cap diameter to about the same extent while 200 Krads appear to have retarded the increase a little more effectively, especially at the lower temperatures (5 and 10°C).

The data in Table 7 show the effects of irradiation dose and storage temperature on the Degree of Opening. The opening was greatly affected by storage temperature for all doses. The control samples, for instance, had D.O.s of .05, .30, and 1.00 after 4 days at 5, 10, and 15°C, respectively. The effect of irradiation dose was also quite evident at all storage temperatures. A dose of 50 Krads reduced the D.O. by a factor of 2 to 4 as compared to control

samples. Doses of 100 and 200 Krads showed a more substantial reduction than did 50 Krads, especially when stored at 10 or 15°C. These doses (100 and 200 Krads) gave about twice the reduction as did 50 Krads at these temperatures.

The measurements of a, d and e made immediately after irradiation and at the end of the storage periods were used to calculate the O.R. values appearing in Table 8. The initial O.R. of 0.35 was then subtracted from the measured O.R.'s and this quantity was divided by the number of days the mushrooms were stored to get the O.R./day, an expression of opening rate. Here again, the storage temperature had a tremendous effect on the rate of cap opening as measured by O.R./day. The Q_{10} of the opening rate was about 7 for the control (0 Krad) mushrooms. Irradiated samples were again appreciably affected by storage temperature but not to the same extent as the controls (Q_{10} of the opening rate about 3.5 to 5.0).

As has been shown in past experiments, the Opening Ratio was greatly affected by irradiation. A 50 Krad dose reduced the O.R./day by a factor of 4.2 at 15°C, 7.3 at 10°C, and 3.2 at 5°C. Doses of 100 and 200 Krads were somewhat more effective than 50 Krads when the mushrooms were stored at 10°C, but the retardation of the opening rate was very similar for all three doses at storage temperatures of 5 and 15°C.

Experiment VIII: The effect of delay between harvest and irradiation.

On January 9, 1968, fresh mushrooms were transported from Warren to East Lansing where they were sorted so that only uniform mushrooms of excellent quality remained. The mushrooms were then placed in coded perforated tubs (20 mushrooms per tub), covered with polyethylene film, and given doses of 0, 50, and 100 Krads after three periods of delay. These irradiations took place at 0.3, 1.3, and 3.3 days after harvest. All mushrooms were stored at 10°C before and after irradiation.

Measurements of a, e, d, and h (mushroom height) were made on groups of 20 non-irradiated mushrooms after 0.3, 1.3, and 3.3 days of storage at 10°C. These measurements were used to estimate the O.R. reached by the lot at each time of irradiation. O.R. measurements were also made at the end of the storage period (7.3 days). Measurements of a, h, and D.O. were made immediately following irradiation and at 7.3 days after harvest. These data were used to calculate the values presented in Tables 9 through 12.

The effects of irradiation dose and a delay between harvest and irradiation on the Degree of Opening is shown in Table 9. The effect of irradiation dose, as in past experiments, is quite evident, with 50 and 100 Krads showing similar reductions in the number of opened caps. The coefficient of variation of the D.O. is quite high (about

Table 9. Degree of Opening of irradiated mushrooms after 7.3 days of storage at 10°C. Average of 20 mushrooms irradiated at 0.3, 1.3, or 3.3 days after harvest.

Dose Krad	Time between harvest and irradiation, days		
	0.3	1.3	3.3
0	0.98	0.99	1.00
50	0.60	0.44	0.86
100	0.30	0.51	0.78

Table 10. Opening Ratio and O.R./day^a of irradiated mushrooms after 7.3 days of storage at 10°C. Average of 20 mushrooms irradiated at 0.3, 1.3, or 3.3 days after harvest.

Dose Krad	Time between harvest and irradiation, days					
	0.3		1.3		3.3	
	O.R.	O.R./day	O.R.	O.R./day	O.R.	O.R./day
0	2.11	0.25	2.12	0.28	1.88	0.31
50	0.70	0.046	0.80	0.062	1.00	0.086
100	0.64	0.037	0.74	0.052	1.09	0.11

^aCalculated between time of irradiation and 7.3 days.

Table 11. Percent increase in height, h , of irradiated mushrooms between the time of irradiation (0.3, 1.3, or 3.3 days after harvest) and 7.3 days after harvest. Average of 20 mushrooms stored in covered perforated tubs at 10°C.

Dose Krad	Time between harvest and irradiation, days		
	0.3	1.3	3.3
0 ^a	22	13	11
50	39	28	12
100	31	26	9

^aThe control (0 Krad) mushrooms had very desiccated stems, probably to the extent that elongation was greatly retarded.

Table 12. Percent increase in cap diameter, a , of irradiated mushrooms between the time of irradiation (0.3, 1.3, or 3.3 days after harvest) and 7.3 days after harvest. Average of 20 mushrooms stored in covered perforated tubs at 10°C.

Dose Krad	Time between harvest and irradiation, days		
	0.3	1.3	3.3
0	17.0	15.0	10.0
50	12.0	3.6	2.8
100	6.8	5.7	1.1

50 percent at a D.O. of 0.8) so that no significant difference between 50 and 100 Krads is evident. A delay between the time of harvest and the time of irradiation resulted in mushrooms with higher D.O.'s; the longer the delay, the less the benefit of irradiation for a given storage period. That is, quality, as exhibited by opening of the cap, cannot be regained by the use of irradiation.

The effects of delay and irradiation dose can be measured by O.R./day. (See Table 10.) In every instance, irradiation doses of 50 and 100 Krads significantly retarded opening of the cap, as measured by O.R. and O.R./day. The O.R./day of control samples (0 Krads) was 6 times the O.R./day of the samples irradiated at 0.3 days, 5 times the O.R./day of those irradiated at 1.3 days, and 3 times the O.R./day of the samples irradiated at 3.3 days after harvest. The magnitude of these factors emphasize the tremendous effect of irradiation on the opening rates of mushrooms. The 100 Krad dose proved to be more effective than the 50 Krad dose when the samples were irradiated at 0.3 and 1.3 days, but perhaps less effective when there was a delay of 3.3 days between harvest and irradiation. The variance in O.R. (about 25 percent at O.R. = 0.8) probably negates the apparent differences between the O.R.'s of the 50 and 100 Krad samples, however.

The decrease in the ratios, O.R./day of controls: O.R./day of irradiated samples, as the delay between harvest

and irradiation is increased--6, 5, and 3 for 0.3, 1.3, and 3.3 days, respectively--suggests that a delay before irradiation renders the treatment less effective. Without a doubt, an irradiation treatment at any of the times tested greatly retards the rate of cap opening, but in order to obtain the most benefit from an irradiation treatment, it should be administered as soon as possible after harvest.

As in Experiment VI, the increase in mushroom height was measured for the storage periods, and is reported in Table 11. At the end of 7.3 days of storage, regardless of when irradiation occurred, the irradiated samples displayed a greater increase in mushroom height than the controls. The 50 Krad samples had increased more than those given 100 Krads. These results are quite different from those observed in Experiment VI in which the 0 Krad samples had increased at approximately the same rate as the 50 Krad samples and much more than the 100 Krad samples. This discrepancy is probably due to the difference in desiccation of the stems of the control (0 Krads) samples compared to those given 50 or 100 Krads. It was noted that the stems of the control samples were very desiccated, probably to the extent that elongation was inhibited. It can also be concluded that elongation occurs most rapidly during the early part of the storage period. Again, this could be connected with desiccation.

The percent increase in cap diameter, a , for the mushrooms tested in this experiment is reported in Table 12. Regardless of the time at which the irradiation treatment was given, mushrooms given 50 or 100 Krads had opened significantly less than the control (0 Krad) mushrooms. The rate of increase was approximately linear for the control samples, but the increase was more rapid during the early part of the storage for the irradiated samples. There was no significant difference between the 50 and 100 Krad treatments when irradiation occurred at 1.3 or 3.3 days, but 100 Krads seemed to be somewhat more effective when the mushrooms were irradiated soon after harvest (0.3 days).

Color

Experiment I: The effect of irradiation dose.

Fresh mushrooms were obtained in Warren and transported to Ann Arbor where they were sorted--only closed mushrooms of good quality were used--into one-pint wooden baskets. Doses of 0, 10, 15, 20, and 50 Krads were each given to eight baskets (irradiation time about 1-1/2 hours). The mushrooms were then transported to East Lansing where they were stored at 3.3°C.

At the end of 2, 7, 15, and 21 days, two pints of each treatment were removed from storage and individual mushrooms were measured with a Gardner color difference meter. The reflectance measurements, as measured by the

L_D values obtained from the Gardner, however, were limited to those mushrooms which were large enough to cover the diaphragm opening of the meter. This greatly limited the number of mushrooms that could be measured to the larger ones in each lot. In addition, it was found that mushrooms with varying diameters protruded into the diaphragm to different depths, further reducing the reliability of this method of measurement.

Table 13 gives the L_D values for irradiated and non-irradiated mushrooms at 2, 7, 15, and 21 days of storage at 3.3°C. The Gardner L_D values did not show a significant difference in reflectance among irradiation treatments. An important observation is, however, that all doses showed a definite darkening (decrease in L_D during storage.

Table 13. L_D values of irradiated mushrooms as determined by a Gardner Color Difference meter. Average of 7 to 10 mushrooms stored at 3.3°C.

Dose Krad	Storage time, days			
	2	7	15	21
0	81.2	78.9	70.9	66.5
10	76.5	80.1	68.5	62.1
15	81.8	69.8	69.2	61.0
20	78.8	74.7	69.5	64.9
50	<u>80.2</u>	<u>71.9</u>	<u>66.6</u>	<u>65.0</u>
Average	79.7	75.1	68.9	63.9

Experiments II through VII:

Due to its poor adaptability, the Gardner color difference meter was not used for later color determinations. Visual observations, however, were made on mushrooms tested in later experiments. It was observed that the rate of mushroom browning was dependent on the extent to which they were in contact with air. If the mushrooms were stored in an open vessel and exposed to rapid air currents, they darkened rapidly. If, however, they were stored in a sealed vessel, the browning rate was greatly retarded.

In general, it was found that irradiated mushrooms, especially those treated with 50 or 100 Krads, did not darken as rapidly as the control (0 Krad) samples. It is the writer's impression, however, that the interior of the stipes of irradiated mushrooms may darken quicker than control samples, but, the difference is not substantial.

Experiment VIII: Panel analysis of color.

Fresh mushrooms transported from Warren to East Lansing on January 9, 1968, were given doses of 0, 50, and 100 Krads and stored at 10°C. At the end of 8 days storage, 9 mushrooms of each dose were placed cap up on egg filler flats and presented in duplicate to 11 judges. They were asked to rate the lots of mushrooms on the basis of darkness, ranking the darkest as 1 and the lightest as 3. The totals for the 22 judgments were 22 for the control (0 Krad) samples, 45 for the 50 Krad samples, and 65 for

the 100 Krad samples. Therefore, the control samples were significantly darker ($P = .01$) than the 100 Krad samples. The judges commented, however, that there was a substantially greater difference in darkness between the control and irradiated samples than between the two lots of irradiated samples.

The conclusion is, then, that irradiation at the levels of 50 and 100 Krads significantly retards the rate of browning of mushroom caps when they are stored at 10°C , as measured by visual examination.

Texture

The texture of many fresh fruits and vegetables has been shown to be adversely affected by irradiation, even at relatively low doses. The instrument used to measure the texture of irradiated and non-irradiated mushrooms was an Allo-Kramer shear press. It must be noted, however, that the values obtained from measurements with this instrument do not necessarily reflect texture in its entirety. The reported data are the peak shear resistances. The units recorded by the Allo-Kramer are microamperes and all measurements were made on 75-gram portions (whole mushrooms) using a 250-pound ring with the instrument range set on 50 and the selector switch set at low.

Experiment IV: The effect of irradiation dose and storage time.

Fresh mushrooms were transported from Warren to East Lansing on April 6, 1967. They were sorted--only medium sized, about 1.3 inch cap diameter, tightly closed mushrooms were used-- and packed in one-quart polyethylene tubs with six 3/8 inch perforations and covered with an unperforated polyethylene film. The samples were given doses of 0, 10, 50, 100, and 500 Krads (4 containers per dose) at the Phoenix Memorial Laboratory on the following morning. On return to East Lansing, the samples were stored at 10°C. Shear resistance was measured on portions of two master samples at one and seven days after irradiation. The average values obtained from four to six portions are reported in Table 14.

Table 14. Peak shear resistance (microamperes)^a of whole mushrooms stored at 10°C. Average of four to six 75 gram portions of two master samples stored in perforated tubs.

Dose Krad	Storage time, days	
	1	7
0	50	51
10	51	54
50	54	49
100	53	50
500	42	42

^aAllo-Kramer shear press, 250 pound ring, range 50, low setting.

An analysis of the data showed that irradiation in the range 10 to 100 Krads (10, 50, and 100 Krads) caused no significant ($P = .05$) change in the shear resistance of fresh whole mushrooms tested at one and seven days after irradiation. However, mushrooms given a dose of 500 Krads had significantly lower ($P = .05$) shear resistances than the other doses at both times tested (averages of 52.3 and 50.9 for all other doses at one and seven days, respectively, compared to 42.1 at both times for the 500 Krad samples). Also, there was no significant difference in shear resistance ($P = .05$) between samples tested at one and seven days, but the 50 and 100 Krad samples suggest that there might be a slight loss in shear resistance during storage.

Experiment VI: The effect of irradiation dose.

Mushrooms harvested early in the morning on November 30, 1967 were transported from Warren to East Lansing where they were carefully sorted to eliminate all defective and opened mushrooms and packed in one-quart perforated polyethylene tubs covered with unperforated film. Doses of 0, 10, 50, 100, 500, and 1,000 Krads were applied with the M.S.U. Food Science gamma facility followed by storage at 5°C. Shear resistance was measured on the following day. The results of these measurements are given in Table 15.

An analysis of variance showed no difference among the shear resistances of the 0, 10, 50, and 100 Krad samples. However, the 500 Krad samples had significantly lower

Table 15. Peak shear resistance (microamperes)^a of irradiated whole mushrooms stored at 5°C. Seventy-five gram portions tested one day after irradiation.

Portion No.	Dose, Krads					
	0	10	50	100	500	1,000
1	49	52	52	52	50	44
2	51	51	53	55	47	43
3	53	53	54	53	47	45
4	<u>49</u>	<u>50</u>	<u>52</u>	<u>49</u>	<u>46</u>	<u>45</u>
Average	50.5	51.5	52.8	52.2	47.5	44.2

^aAllo-Kramer shear press, 250 lb. ring, range 50, low setting.

values (about 10 percent) than the lower doses ($P = .01$) and the 1,000 Krad samples had significantly lower shear resistances (about 5 percent) than the 500 Krad samples ($P = .05$) or the lower doses ($P = .01$).

Respiration

The respiratory activity of many living commodities has been directly associated with the changes which occur during storage. The primary concept and successful application of controlled atmosphere storage of apples and other fresh fruits and vegetables hinges on the ability of this method to retard the respiratory rate. Therefore, it was logically assumed that the effect of irradiation in slowing down certain physiologic changes in mushrooms might be the results of a retardation in the rate of respiration.

As was stated in the introduction, Mercier and MacQueen (1965) found an initial acceleration in the rate of CO₂ evolution (caused by irradiation), but after one day, non-irradiated mushrooms showed a higher respiration rate than those that were irradiated. Their measurements of the CO₂ evolution were made with an infra-red CO₂ analyzer, but it was not stated whether an open or closed system was used. The rate of evolution of their control samples was about 200 grams CO₂/gram-hour (10.2 ml CO₂/100 gram-hour) at room temperature four hours after irradiation.

The effects of using a closed (i.e. sealed container) rather than an open (gas flow) system can be important. The open system has the definite advantage of avoiding accumulation of carbon dioxide gas or an excessive depletion of oxygen within the container. Either of these occurrences could drastically alter the respiration rate of samples when it is determined in a closed system.

Experiment II: The effect of dose and storage temperature.

On January 12, 1967, fresh mushrooms were transported from Warren to Ann Arbor where they were sorted to eliminate any mushrooms other than those of medium size and tightly closed caps. Ten mushrooms were placed in each of 75 wooden pint baskets and doses of 0, 10, 20, 50, and 100 Krads were each given to 15 of these baskets. All samples were returned to East Lansing and stored at 3.3°C.

During the following morning, the mushrooms were taken to the Horticulture Building of M.S.U. where they were prepared for respiration rate measurements. Each dose level was tested in triplicate while stored at three temperatures; 5, 10, and 15°C. Ten mushrooms were placed in each of the tared pails to be stored at 15°C, 15 mushrooms in each of those stored at 10°C, and 20 mushrooms in each of those stored at 5°C. More mushrooms were placed in the containers to be held at lower temperatures in order to compensate for the lower rate (per unit weight) of respiration at lower temperatures. Each pail was provided with a top equipped with an inlet and exhaust. The exhaust was designed to remove gases from near the bottom of the pail and the inlet allowed gases to enter near the top of the pail. This was an open (flow type) system which did not allow build-up of CO₂ or depletion of O₂.

During the entire storage period, air monitored for CO₂ and O₂ content was passed through each pail at a measured and constant rate. Then, at 12 hour intervals, the exhaust gases from each pail were monitored by automatic O₂ and CO₂ analyzers so that the rates of exchange of these gases could be calculated. Therefore, since the weight of mushrooms in each pail was known, the rate of gas exchange per unit weight could be calculated. The equipment and method of analysis used in this experiment are described by Dilley (1966).

Tables 16 through 18 give the results of the measurements described above. Each reported value is the average volume of gas (three replicate samples) exchanged by 100 grams of mushrooms in one hour.

Curves of the gas exchange rate versus time were drawn from each of these tables. As expected, it was found that temperature had the most pronounced effect on the rate of respiration. Q_{10} at 0.5 days was calculated to be 4.4, as determined by the rate of CO_2 gas exchange.

Simpson's method of approximate integration (Simpson's rule) was used to calculate the cumulative respiration of the mushrooms over the first four days of testing. The values obtained by this method were the volume (milliliters) of gas exchanged by 100 grams of mushrooms during a period of 96 hours. Calculations were made for each dose at each storage temperature. Tables 19 through 21 contain the results of these calculations.

An analysis of variance was applied to these tables and it was found that there was a significant difference ($P = .05$) between the respiration rate of the control (0 Krad) and irradiated samples when stored at 15°C . There was no significant difference, however, among the irradiation doses. There was no significance (statistically) among treatments when they were stored at 5 or 10°C , but an evaluation of the curves drawn from Table 17 strongly suggests

Table 16. Respiration rates, ml gas exchanged/100 gram-hour,^a of irradiated mushrooms stored at 5°C. Average of three replicate samples containing 20 mushrooms each.

Dose Krad	Gas	Time, hours ^b										
		0	12	24	36	48	60	72	84	96	108	Average
0	CO ₂	3.2	2.7	2.9	3.2	3.2	3.2	3.2	3.2	3.4	3.3	3.2
	O ₂	3.6	3.3	3.3	3.5	3.8	3.8	3.8	3.9	3.7	3.8	3.6
10	CO ₂	3.5	3.1	3.2	3.4	3.3	3.1	3.0	3.3	3.0	2.9	3.2
	O ₂	3.9	3.7	3.7	4.1	3.6	3.9	3.7	3.7	3.5	3.6	3.7
20	CO ₂	3.6	3.1	3.3	3.5	3.4	3.3	3.2	3.1	3.1	3.0	3.3
	O ₂	3.7	3.7	3.6	3.7	3.8	4.1	3.8	3.8	3.3	3.7	3.7
50	CO ₂	3.4	2.8	2.9	3.1	3.3	3.1	2.9	2.9	2.9	2.8	3.0
	O ₂	3.4	3.2	3.2	3.4	3.4	3.8	3.5	3.5	3.3	3.5	3.4
100	CO ₂	3.4	2.7	2.9	3.1	3.1	3.0	3.0	2.9	3.0	3.0	3.0
	O ₂	3.5	3.2	3.2	3.2	3.4	3.7	3.6	3.5	3.4	3.5	3.4

^aGas volumes reported at standard temperature and pressure.

^bTime 0 is the time at which gas analysis began, or, one day after irradiation.

Table 17. Respiration rates, ml gas exchanged/100 grams-hour,^a of irradiated mushrooms stored at 10°C. Average of three replicate samples containing 15 mushrooms each.

Dose Krad	Gas	Time, hours ^b										
		0	12	24	36	48	60	72	84	96	108	Average
0	CO ₂	4.9	5.7	6.5	5.7	6.5	6.4	6.5	6.5	6.5	6.6	6.3
	O ₂	5.9	6.4	7.4	7.7	7.5	7.1	7.3	7.4	7.4	7.2	7.1
10	CO ₂	6.2	6.5	6.6	6.6	6.1	5.8	5.7	5.5	5.2	5.2	5.9
	O ₂	7.5	7.4	7.7	8.2	7.7	6.9	6.7	6.8	6.5	6.1	7.2
20	CO ₂	5.6	6.1	6.1	6.2	5.6	5.3	5.1	4.9	4.8	4.6	5.4
	O ₂	6.7	6.6	6.8	7.1	7.1	6.2	6.3	6.1	5.8	5.3	6.4
50	CO ₂	5.8	6.1	6.2	6.2	5.8	5.6	5.2	5.2	4.8	4.7	5.6
	O ₂	6.4	6.6	6.8	7.0	7.0	6.3	6.3	6.3	5.8	5.8	6.4
100	CO ₂	5.1	5.5	5.7	5.8	5.4	5.3	5.0	4.9	4.6	4.5	5.2
	O ₂	5.8	5.8	6.3	6.6	6.7	6.0	6.2	6.1	5.7	5.2	6.0

^aGas volumes reported at standard temperature and pressure.

^bTime 0 is the time at which gas analysis began, or, one day after irradiation.

Table 18. Respiration rates, ml gas exchanged/100 gram-hour,^a of irradiated mushrooms stored at 15°C. Average of three replicate samples containing 10 mushrooms each.

Dose Krad	Gas	Time, hours ^b										
		0	12	24	35	48	60	72	84	96	108	Average
0	CO ₂	10.9	13.2	12.6	12.4	11.2	10.5	9.4	10.4	10.4	10.8	11.2
	O ₂	12.6	14.4	14.5	13.5	13.3	12.9	11.3	12.1	12.4	11.9	12.9
10	CO ₂	11.8	12.9	10.8	10.1	8.8	8.0	7.2	7.2	6.7	6.5	9.0
	O ₂	13.7	14.0	12.7	11.6	10.6	9.8	9.2	8.9	8.4	7.7	10.7
20	CO ₂	11.7	12.6	10.8	9.7	8.5	8.0	7.3	7.0	6.5	6.2	8.8
	O ₂	13.6	13.9	12.9	11.3	10.4	9.9	9.8	8.7	8.3	7.5	10.6
50	CO ₂	11.2	11.4	10.7	9.5	8.0	7.2	6.5	6.5	6.1	5.7	8.3
	O ₂	12.7	12.9	12.4	11.1	9.7	9.1	8.2	8.0	7.8	6.8	9.9
100	CO ₂	11.0	11.9	11.3	10.3	8.6	8.1	7.4	7.0	6.7	6.4	8.9
	O ₂	12.3	12.7	12.7	12.5	10.5	9.8	10.0	8.6	8.1	7.2	10.4

^aGas volumes reported at standard temperature and pressure.

^bTime 0 is the time at which gas analysis began, or, one day after irradiation.

Table 19. Cumulative respiration,^a ml gas exchanged per 100 grams during the first 96 hours of testing,^b of mushrooms stored at 5°C.

Replicate No.	Gas	Dose, Krads				
		0	10	20	50	100
1	CO ₂	285	286	315	288	296
	O ₂	340	364	358	328	339
2	CO ₂	295	317	306	299	281
	O ₂	356	379	378	359	322
3	CO ₂	309	306	315	274	284
	O ₂	<u>352</u>	<u>345</u>	<u>349</u>	<u>305</u>	<u>316</u>
Total	CO ₂	889	909	936	861	861
	O ₂	1,047	1,088	1,082	992	978

^aGas volumes at standard temperature and pressure.

^bCumulative respiration calculated by Simpson's method of approximate integration (Simpson's Rule).

Table 20. Cumulative respiration,^a ml gas exchanged per 100 grams during the first 96 hours of testing, of mushrooms stored at 10°C.

Replicate No.	Gas	Dose, Krads				
		0	10	20	50	100
1	CO ₂	611	675	530	540	542
	O ₂	697	822	633	630	622
2	CO ₂	610	579	550	606	542
	O ₂	699	693	646	690	626
3	CO ₂	600	504	524	505	553
	O ₂	667	594	614	590	534
Total	CO ₂	1,821	1,758	1,604	1,651	1,538
	O ₂	2,063	2,109	1,892	1,910	1,782

^aGas volumes at standard temperature and pressure.

^bCumulative respiration calculated by Simpson's method of approximate integration (Simpson's Rule).

Table 21. Cumulative respiration,^a ml gas exchanged per 100 grams during the first 96 hours of testing, of mushrooms stored at 15°C.

Replicate No.	Gas	Dose, Krads				
		0	10	20	50	100
1	CO ₂	1,035	858	812	852	827
	O ₂	1,151	1,007	968	1,008	988
2	CO ₂	1,253	903	830	792	815
	O ₂	1,431	1,082	1,013	834	983
3	CO ₂	1,031	938	998	850	1,010
	O ₂	<u>1,204</u>	<u>1,226</u>	<u>1,162</u>	<u>979</u>	<u>1,344</u>
Total	CO ₂	3,319	2,699	2,641	2,494	2,651
	O ₂	3,786	3,314	3,144	2,822	3,316

^aGas volumes at standard temperature and pressure.

^bCumulative respiration calculated by Simpson's method of approximate integration (Simpson's Rule).

that there is a real difference in the respiratory activities of the control and irradiated samples at 10°C. The curves drawn from Table 16 substantiate the results obtained from the analysis--that is, there is no difference in the rate of respiration between controls and irradiated samples when they are stored at 5°C.

All treatments held at 10 and 15°C showed an increase in respiration rate during the first 0.5 day. However, between 0.5 and 4.5 days the respiration rates of these samples decreased, with the irradiated samples falling off more rapidly than the controls.

It can be concluded, then, that the rate of cap opening and the rate of respiration are retarded by an irradiation treatment, and, the magnitude of these effects is temperature dependent. Therefore, it is very possible that the retardation of the respiration rate is directly related and possibly a contributor to the retardation in the rate of cap opening and other changes which occur during storage.

Halevy et al. (1965) applied various chemical treatments to fresh mushrooms in an attempt to reduce the rate of respiration. The respiratory rate of Alar (N, N-dimethylaminosuccinamic acid) treated mushrooms was reduced when the mushrooms were stored at 20°C but not with storage at 10°C. B A (⁶N-Benzyladenine) promoted CO₂ evolution at

both temperatures while C C C (2-chloroethyltrimethylammonium chloride) and sodium bisulfite slightly reduced the respiratory rate but only at the higher temperature. The average rate of CO_2 evolution for the control samples stored at 10°C was about $5.5 \text{ ml } \text{CO}_2/100 \text{ g-hour}$ (range 4.6-6.3).

Wright et al. (1963) give the heat evolution of cultivated mushrooms stored at 50°F (10°C) as 22,000 B.T.U./ton-24 hours. This value, in terms of respiration rate, is equivalent to about $5.1 \text{ ml } \text{CO}_2/100 \text{ g-hour}$.

The average rate of CO_2 evolution in this experiment, during the first 24 hours of control mushrooms stored at 10°C (see Table 17), was about $5.7 \text{ ml } \text{CO}_2/100 \text{ g-hour}$ (range 4.9-6.5). The rates of respiration of mushrooms in the two references cited, then, are similar to the rate of control mushrooms in this experiment. Also, the effect of temperature on the retardation of the respiratory rate caused by Halevy's chemical treatments was similar to the temperature effect on the retardation caused by the irradiation treatment.

The respiratory quotients (ratios of CO_2 evolved to O_2 consumed) were calculated for each treatment and are reported in Table 22.

The respiratory quotient was not appreciably altered (Ave = 0.85) by temperature in the range 5 to 15°C (5, 10,

and 15°C) or by irradiation dose in the range 10 to 100 Krads (10, 20, 50, and 100 Krads). Similarly, Halevy et al. (1965) found, "No chemical treatment affected the RQ which ranged from 0.87 to 0.89."

Table 22. Respiratory quotients^a (ratio of CO₂ evolved to O₂ consumed) for irradiated mushrooms held at 5, 10, and 15°C for 4.5 days.

Temperature of Storage, °C.	Dose, Krads					Average
	0	10	20	50	100	
5	.85	.84	.86	.87	.88	.86
10	.88	.83	.85	.86	.86	.86
15	<u>.88</u>	<u>.81</u>	<u>.84</u>	<u>.88</u>	<u>.80</u>	<u>.84</u>
Average	.87	.83	.85	.87	.85	.85

^aCalculated from the data appearing in Tables 19 through 21.

Transpiration

Experiment III: The effect of container style and storage temperature.

Fresh mushrooms were transported from Warren to Ann Arbor where they were sorted--only mushrooms of good

quality and tightly closed caps were used--and packed into four styles of containers.

- 1) A commercial, one-quart, polyethylene cottage cheese tub (5.5 inches high, 4.0 inches inside top diameter) with no cover,
- 2) The same tub as in (1), but, covered with polyethylene film having four 1/4 inch perforations.
- 3) The same tub as in (1), only covered with an unperforated polyethylene film,
- 4) A commercial (5 in. x 7 in. x 2 in.) one-pound mushroom box coated internally with wax film and having ten 7/16 inch diameter perforations (four on both top and bottom and one on each end).

Doses of 0, 10, and 100 Krads were administered during a one hour period using the Co-60 source housed in Phoenix Memorial Laboratory, Ann Arbor.

On return to East Lansing, the containers were stored in two temperature controlled boxes at temperatures of 5 and 15°C. The air flow over the containers was measured to be about 36 feet/minute and the relative humidity was about 70 percent. The containers in the 15°C cabinet were weighed at 1, 2, 4, 6, and 7 days after irradiation, and those stored in the 5°C cabinet were weighed after 1, 2, 5, 6, 8, and 10 days. The percent weight losses calculated from these weighings are presented in Table 23.

Table 23. Percent weight loss (wet basis) of irradiated mushrooms. Average of three replicate samples stored at 5 and 15°C.

Container Style	Dose Krad	Storage time, days						
		1	2	4	6	7	8	10
At 5°C:								
1. Open tub	0	6.4	11.6	24.1	32.4	---	43.6	49.7
	10	6.1	11.1	20.5	29.6	---	38.0	45.3
	100	5.6	11.2	25.5	31.6	---	39.9	46.6
2. Tub with per- forated top	0	0.6	0.8	2.6	3.8	---	6.9	7.7
	10	0.9	1.8	3.3	4.3	---	5.7	7.0
	100	0.8	1.4	3.1	4.3	---	5.7	7.0
3. Sealed tub with no per- forations	0	0.1	0.1	0.2	0.3	---	0.5	0.6
	10	0.1	0.2	0.3	0.4	---	0.4	0.6
	100	0.1	0.1	0.3	0.4	---	0.4	0.6
4. Commercial box	0	6.8	12.4	27.0	37.3	---	47.3	55.6
	10	6.6	12.3	27.2	35.9	---	45.6	55.2
	100	6.8	13.7	25.4	33.9	---	43.8	55.4
At 15°C:								
1. Open tub	0	6.6	15.4	38.5	52.5	55.8	---	---
	10	8.2	17.9	38.9	48.9	54.0	---	---
	100	12.4	20.2	37.4	47.0	52.2	---	---
2. Tub with per- forated top	0	0.9	1.9	4.7	6.2	7.1	---	---
	10	1.0	2.1	4.2	6.4	6.5	---	---
	100	0.9	1.8	3.8	6.2	6.2	---	---
3. Sealed tub with no per- forations	0	0.1	0.2	0.5	0.8	0.9	---	---
	10	0.1	0.2	0.5	0.7	0.8	---	---
	100	0.1	0.2	0.5	0.6	0.7	---	---
4. Commercial box	0	8.4	16.8	36.8	47.2	55.3	---	---
	10	8.2	17.0	35.0	47.9	54.1	---	---
	100	9.5	17.7	37.1	50.3	56.6	---	---

The irradiation dose had no significant effect on the rate of weight loss under the conditions of this experiment. However, the style of container and the storage temperature had a pronounced effect on the weight loss (water loss through transpiration) of the mushrooms. The mushrooms stored in container styles 1 and 4--the one-quart cottage cheese tub with no cover and the commercial one-pound mushroom box--lost about 50 percent of their weight whether stored for 7 days at 15°C or 10 days at 5°C. The cottage cheese tub with the perforated top allowed about 7 percent loss during this time while the mushrooms in the sealed tub loss less than 1 percent of their weight.

At the end of the two storage periods (7 days at 15°C and 10 days at 5°C), the mushrooms were removed from storage and subjected to a visual quality examination and measurement of the D.O. All treatments were evaluated as to the degree of desiccation, mold growth (as determined by the presence of mold mycelia or slime mold), color (measured subjectively by visual examination), and odor (again measured subjectively).

Storage at 5°C for 10 days: When stored at 5°C the mushrooms retained overall quality better when they were stored in the tub with the perforated top or in the sealed tub. The best lot in all the treatments was that given 100 Krads of irradiation and stored in the tub with the perforated top. The Degree of Opening was effected by

the irradiation dose and the style of container. Container styles 3 and 4 did not allow any opening of the cap as measured by D.O., but the control samples stored in styles 1 and 2 opened to a D.O. of 0.2 and the 10 Krad samples stored in style 2 opened to a D.O. of 0.1.

Container styles 1 and 4 allowed extensive desiccation of the mushrooms, but the desiccation was not affected by irradiation dose. There was no apparent mold growth with any treatment, but this was more than likely due to the low storage temperature rather than to the treatments. The mushrooms stored in container styles 1 and 4 were darker than those stored in the other containers. This darkening is probably directly connected with the extreme desiccation allowed by these containers. Irradiation doses of 10 and 100 Krads retarded browning in container styles 2 and 3, with the 100 Krad dose showing the least browning.

There was no unpleasant odor detected in containers 1 and 4 (again probably a result of desiccation), but there was an off-odor detected in all the control (0 Krad) and 10 Krad samples stored in styles 2 and 3 and in the 100 Krad samples stored in style 3. The odor was more pronounced in the control (0 Krad) samples in both instances.

Storage at 15°C for 7 days: When stored at 15°C, the mushrooms again retained their quality better when they were stored in container styles 2 and 3. However, the keeping quality in a given container style was more affected by

irradiation dose at this temperature. The 0 Krad samples did not keep well in any container. The 10 and 100 Krad samples kept best in styles 2 and 3 with the 100 Krad samples showing much better quality retention than the 10 Krad samples.

Container style 3 did not allow opening of the caps, again as measured by the Degree of Opening. The sealed containers apparently allowed a build-up of CO₂ and a depletion of O₂, thus, in effect, "suffocating" and therefore retarding or preventing at least some of the physiological activities. Container 1 allowed the 0 and 10 Krad samples to reach D.O.'s of 1.0 but the 100 Krad samples only opened to 0.1. The D.O.'s in style 2 were 1.0, 0.9, and 0.1 for 0, 10, and 100 Krads, respectively, and style 3 allowed extensive opening of the 0 and 10 Krad samples (D.O. = 1.0) but no opening of the 100 Krad mushrooms (D.O. = 0.0).

The transpiration losses were similar to those observed in the treatments held at 5°C for 10 days, that is, container styles 1 and 4 allowed extensive desiccation while styles 2 and 3 yielded a better retention of water. The mold growth, however, was substantial at this temperature. Mold mycelia were apparent on the 0 and 10 Krad samples stored in container style 1. There was no apparent slime developed in containers 2 and 3 with the 100 Krad samples showing less development than the 0 and 10 Krad samples and style 3 showing a greater abundance of mold

than style 2. The mushrooms stored in container style 4 showed no apparent mold (again due to the excessive desiccation of the mushrooms).

The rate of darkening was affected by both the irradiation dose and the container style. Irradiation substantially retarded the rate of browning with 100 Krads having a much greater effect than 10 Krads. The irradiated samples showed less darkening when stored in styles 2 and 3. Mushrooms given 100 Krads of irradiation and stored in container style 2 showed the least browning.

There was no detectable unpleasant odor in any mushrooms stored in container styles 1 and 4 or by any mushrooms given a 100 Krad dose regardless of the storage container. Mushrooms given 0 and 10 Krad doses and stored in styles 2 and 3, however, had an extremely unpleasant odor with the control samples stored in style 3 having the most pronounced odor.

Experiment IV: The effect of container style on transpiration.

On April 6, 1967, fresh mushrooms were transported from Warren to East Lansing where they were sorted (only medium sized, about 1.3 inch diameter, tightly closed mushrooms were used) and randomly placed into five container styles.

- 1) One-quart polyethylene tub with no cover,
- 2) One-quart polyethylene tub, open end covered with unperforated polyethylene film,

- 3) One-quart polyethylene tub with six 3/8-inch diameter perforations (three at 1-1/2 inches from top and three at 1-1/2 inches from bottom) and covered with unperforated polyethylene film,
- 4) Commercial 1-pound mushroom box having internal wax coating and ten 7/16 inch diameter perforations (four on top and bottom and one on each of the two sides),
- 5) Modified commercial box, the same as in (4), but with the perforations reduced to 1/4 inch diameter.

The samples were given doses (two containers per dose) of 0, 10, and 100 Krads on the following morning at the Phoenix Memorial Laboratory, Ann Arbor. On return to East Lansing, the containers were placed in temperature controlled boxes at 10°C.

All containers plus mushrooms were weighed at 0 and 7 days after irradiation and the percent weight loss (wet basis) was calculated. The D.O. was also measured at this time. These results are reported in Table 24.

The data presented here again show no effect of irradiation dose on the rate of transpiration, and, as before, the D.O. was affected by irradiation dose. In all cases, the 100 Krad samples opened less than did the control samples. The 10 Krad samples also opened less than did the controls except when they were stored in the commercial box (both at D.O. = 1.00).

Table 24. Percent weight loss and D.O. of mushrooms stored for 7 days at 10°C in various container styles.^a

Container Style		Dose, Krads					
		0		10		100	
		% Wt. Loss	D.O.	% Wt. Loss	D.O.	% Wt. Loss	D.O.
Open tub	(1)	29.1	1.00	24.2	0.50	26.9	0.10
Sealed tub	(2) ^a	0.7	0.50	0.8	0.30	0.5	0.34
Perforated tub	(3)	7.1	1.00	6.6	0.66	4.8	0.54
Commercial box	(4) ^a	21.0	1.00	22.1	1.00	19.2	0.36
Modified comm. box	(5)	18.2	1.00	17.6	0.95	17.8	0.47

^aThe D.O. and percent weight loss are the average of two containers (about 50 mushrooms) except as noted where one container (about 25 mushrooms) was measured.

The style of container in which the mushrooms were stored affected both the transpiration rate and the D.O. (This result confirms that obtained in Experiment III.) The open tub allowed the greatest desiccation (24-29 percent) and the sealed tub allowed the least (0.5-0.8 percent). The reduction in the size of the perforations in the commercial box (style 5) reduced the amount of transpiration by only 3 percent in the seven-day storage period although the total open area was reduced by more than one-half. The mushrooms stored in the perforated tubs lost 4.8 to 7.1 percent of

their weight during storage and seemed to show a better retention of quality than those stored in other container styles.

Storage in the sealed containers (style 2) greatly retarded the opening of the cap as measured by D.O. The control (0 Krad) mushrooms stored in this container style opened only to a D.O. of 0.50 (this, again, was probably a result of "suffocation" of the mushrooms). The other containers affected the opening in various ways, but all controls were opened to D.O. = 1.00 and the irradiation affected the opening differently for each container style.

The substantial effect of container style on the quality of mushrooms observed in Experiments III and IV suggested that the choice of the style of container for following experiments could have a pronounced effect of the quality factors under investigation. It was decided that, of the containers tested, the perforated one-quart polyethylene tub covered with unperforated polyethylene film showed the best retention of mushroom quality.

Experiment VI: The effect of irradiation dose and storage time.

Fresh mushrooms were transported from Warren to East Lansing on November 30, 1967. All defective and opened mushrooms were discarded and the remaining mushrooms were placed in perforated one-quart polyethylene tubs (see container style No. 3 in Experiment III) covered with an

unperforated polyethylene film. Doses of 0, 10, 20, 50, and 100 Krads were then applied using the M.S.U. Food Science gamma facility. Following irradiations, the mushrooms were re-sorted, leaving only mushrooms of uniform size, shape, and tightness of cap. Fifteen mushrooms of each dose were placed stem up on paperboard egg filler flats with numbered slots (two doses per flat). The flats were covered with unperforated polyethylene bags and stored at 10°C in a temperature controlled cubicle. Each mushroom was weighed at 0, 2.0, 4.1, 7.0, and 11.0 days after irradiation. The percent decrease in weight (from time 0) was calculated and the average values for 15 mushrooms are reported in Table 25.

Table 25. Percent decrease in weight of irradiated mushrooms during storage at 10°C. Average of the same 15 mushrooms, for each treatment, throughout the storage period.

Dose Krad	Storage time, days			
	2.0	4.1	7.0	11.0
0	6.0	8.6	11.3	14.9
10	6.7	12.1	15.8	19.7
20	5.6	7.7	14.9	17.1
50	5.3	7.0	12.0	14.6
100	6.9	9.8	13.0	15.4

An analysis of variance of the data taken at 7 days storage showed the 10 and 20 Krad samples to have a significantly greater weight loss than those treated with 0, 50, and 100 Krads. The variances within samples were not similar, however, so that the validity of the analysis is questionable. Nevertheless, these data suggest that low irradiation doses (10 and 20 Krads) enhance or increase the rate of weight loss while higher doses (50 and 100 Krads) offset this increase and have a loss rate similar to that of control samples.

Experiment VII: The effect of storage temperature.

On December 18, 1967, fresh mushrooms were transported from Warren to East Lansing where they were carefully sorted to assure that only uniform mushrooms of excellent quality were tested. The mushrooms were placed into perforated one-quart polyethylene tubs and doses of 0, 50, 100, and 200 Krads were administered using the M.S.U. Food Science gamma facility. Following irradiation, all mushrooms were individually weighed and placed into numbered chipboard egg filler flats (15 mushrooms per treatment) covered with an unperforated polyethylene bag and placed in temperature controlled cubicles at 5, 10, and 15°C.

The mushrooms stored at 15°C were again weighed at 1.0, 2.0, 3.0, and 4.0 days after irradiation; those stored at 10°C were weighed at 2.0, 4.0, 8.0, 11.0, and 15.0 days after irradiation; and those stored at 5°C were weighed at

4.0, 8.0, 15.0, and 21.0 days after irradiation. These data were used to calculate the percent weight loss at the various time intervals. The results of these calculations are presented in Table 26.

Table 26. Percent weight loss of irradiated mushrooms. Average of 15 mushrooms at each treatment; the same mushrooms were measured throughout the storage periods.

Dose Krad	Storage Temp., °C	Storage time, days							
		1.0	2.0	3.0	4.0	8.0	11.0	15.0	21.0
0	5	---	---	---	5.5	8.9	---	12.0	16.0
	10	---	4.1	---	6.9	12.0	19.0	22.0	---
	15	4.0	7.7	9.9	14.0	---	---	---	---
50	5	---	---	---	5.7	9.0	---	13.0	16.0
	10	---	4.7	---	8.4	14.0	16.0	19.0	---
	15	6.0	13.0	16.0	22.0	---	---	---	---
100	5	---	---	---	5.3	8.3	---	14.0	16.0
	10	---	4.9	---	7.0	9.0	13.0	14.0	---
	15	5.7	8.8	11.0	15.0	---	---	---	---
200	5	---	---	---	5.3	7.9	---	18.0	22.0
	10	---	6.3	---	9.3	12.0	14.0	20.0	---
	15	4.4	7.5	10.0	15.0	---	---	---	---

The effects of irradiation dose and storage temperature on the rate of weight loss were analyzed, resulting in the following conclusions. The rate of weight loss, as expected, increased with an increase in temperature: about 4%/day at 15°C, 1.3%/day at 10°C, and 0.8%/day at 5°C.

The effect of irradiation dose on weight loss was not clear and the observed effect varied with temperature.

The mushrooms stored at 5°C showed no difference in the rate of weight loss between 0, 50, and 100 Krad treatments, but between 8 and 15 days of storage, the 200 Krad samples lost about 10 percent of their weight, giving them a significantly higher overall rate. The reason for this occurrence is not clear, but it may have been a result of positioning during storage or other unknown factors.

When stored at 10°C, the 0, 50, and 200 Krad samples lost weight at approximately the same rate, but the 100 Krad samples seemed to have a somewhat slower rate. Again, the reason for this is uncertain.

Still a different pattern was observed in the mushrooms stored at 15°C. The 0, 100, and 200 Krad samples had similar rates of weight loss, but the 50 Krad samples had a significantly higher rate (3.8%/day versus 5.5%/day). As before, the reason for this difference is unclear in light of the results observed at the other temperatures.

Experiment VIII: The effect of delay between harvest and irradiation.

On January 9, 1968, fresh mushrooms were transported from Warren to East Lansing where they were sorted so that only uniform mushrooms of excellent quality remained. The mushrooms were then placed into perforated one-quart polyethylene tubs (20 mushrooms per tub), covered with polyethylene film, and given doses of 0, 50, and 100 Krads after three time intervals. These irradiations took place at 0.3,

1.3, and 3.3 days after harvest. All mushrooms were stored at 10°C before and after irradiation. Each mushroom was weighed immediately following irradiation and at 7.3 days after harvest. These data were used to calculate the percent weight loss for the three storage intervals. The results are reported in Table 27.

Table 27. Percent weight loss between the time of irradiation (0.3, 1.3, or 3.3 days after harvest) and 7.3 days after harvest. Average of 20 mushroom stored in covered perforated tubs at 10°C.

Dose Krad	Time of irradiation, days		
	0.3	1.3	3.3
0	19	16	11
50	9	18	13
100	10	12	17

The results of this experiment are again inconclusive. There is no consistency within the data as related to irradiation dose or the delay before irradiation. A number of factors could have contributed to this variability including positioning within the cubicle, arrangements within the tubs, temperature fluctuations, and sampling errors.

DISCUSSION AND CONCLUSIONS

Transpiration

Fresh mushrooms suffer a substantial loss of quality if they are allowed to become excessively dehydrated. The skin of the cap and stem becomes shriveled, browning is accelerated, and a number of post-harvest physiological activities are altered. Physiological changes that may be altered by desiccation and serve to affect the parameters O.R. and D.O. and the apparent quality of mushrooms are 1) the stem decreases in diameter at a faster rate, 2) the cap stops opening and may even become smaller in diameter, 3) the veil becomes less elastic and separates at an earlier stage of cap opening, and 4) stem elongation is retarded. If desiccation is severe enough, the mushroom caps will not open at all.

The effect of irradiation on the rate of transpiration is not clear. The effect of dose was different for various experimental conditions so that the effect of irradiation, if there is one, is subtle and elusive. Experiment VI showed doses of 10 and 20 Krads to accelerate significantly the rate of transpiration, while doses of 0, 50, and 100 Krads gave similar rates of water loss. There

was no significant effect caused by irradiation in Experiments III, IV, VII, and VIII. The rates of transpiration among treatments in these experiments was different so that the effect of irradiation on this quality factor is inconclusive. The effect, if it exists, is apparently overshadowed by other experimental factors such as storage container, temperature, positioning of the mushrooms within the containers and positioning the containers in the storage rooms, conditions of handling, and relative humidity of the storage atmosphere.

The factors which have the most effect on the rate of transpiration are the temperature and relative humidity, the factors which define the vapor pressure deficit for a given storage condition. The rate of air flow over the surface of a commodity is, of course, also very important in determining the rate of transpiration. It is necessary to package mushrooms in a container that will keep the vapor pressure deficit low as well as prevent excessive exposure to air drafts. However, as was shown in Experiments III and IV, it is essential that there be adequate ventilation so as to prevent "suffocation" of the mushrooms and at the same time avoid optimum conditions for microbial growth.

Apart from the effects of water loss on quality per se, the resulting economic loss is very important. Any water lost during warehousing or marketing, and this could well be about 25 percent of the original weight, is

water that cannot be sold to the consumer at the going rate for mushrooms. The effect of this loss on profit is probably substantial. (The mushrooms stored in commercial boxes lost more than 50 percent of their weight in 7 days at 15°C.)

Color

Darkening of mushrooms during storage has an important effect on the appearance. Browning is accelerated by excessive desiccation and by handling and other sources of bruising.

Even though it did measure a darkening of all treatments during storage, the Gardner color difference meter was not satisfactory for accurate measurements of the reflectance, L_D , of mushroom caps. As a result, a panel of judges was used to test the effect of irradiation on the color of mushrooms. The judges significantly ($P = .01$) chose the unirradiated samples as the darkest when compared to mushrooms given 50 and 100 Krads of irradiation. The higher dose, 100 Krads, gave better retention of the white color, but certainly not in proportion to the additional dose.

Respiration

The results of Experiment II were in general agreement with the findings of Mercier and MacQueen (1965).

They found that irradiation caused an initial increase in CO₂ evolution, but by the end of one day, the unirradiated samples had the highest activity (measurements made at room temperature).

The data in Experiment II show that irradiation doses in the range 10 to 100 Krads reduce the respiration rate of fresh mushrooms when they are stored at 15°C. The data also suggest that there is a reduction in the respiration rate of irradiated mushrooms held at 10°C. Irradiation has no evident effect on the respiration rate of mushrooms stored at 5°C. Indeed, there is little respiratory activity at this temperature; the rate of CO₂ evolution at this temperature was about 2.6 ml CO₂/100 g-hour. The respiratory quotient was not appreciably altered by temperature in the range 5 to 15°C or by irradiation dose in the range 10 to 100 Krads. A tentative explanation is that neither temperature nor radiation alters the overall respiratory scheme, just its rate.

Texture

The texture of fresh mushrooms, as measured by the peak shear resistance, was unaffected by irradiation doses up to 100 Krads (10, 50, and 100 Krads). A dose of 500 Krads significantly lowered the peak shear resistance by about 10 percent and a dose of 1,000 Krads caused a decrease of about 15 percent. The importance of this

reduction with respect to overall quality is not known. Also, it should be noted that while a dose of 500 Krads is necessary to give a noticeable reduction of shear resistance in mushrooms, a dose of 200 Krads is enough to give a similar loss of shear resistance in strawberries, blueberries, and other fruits. The mechanism for the loss must, therefore, be different and has yet to be explained.

Since 500 Krads is considerably higher than a dose that is likely to be recommended or to be necessary to retard many of the deleterious changes in mushrooms, the effect of irradiation on texture can probably be considered unimportant.

Dimensional Changes

The changes in the physical dimensions of mushrooms which occur during storage give the greatest impression of loss of freshness. The two changes which affect O.R. and D.O. are the opening of the cap resulting in an increase in cap diameter and shrinking of the stem diameter. These changes together result in a larger opening gap--the quantity $(b + c)$ or $(e - d)$ in the opening ratio becomes larger (see Fig. 3). Nevertheless, the end result is separation of the veil and excessive exposure of the dark gills. The importance of stem elongation on the quality of mushrooms has not been established, but it is generally felt that this change is deleterious to the appearance of mushrooms.

Storage temperature has a tremendous effect on the rate of the dimensional changes in mushrooms. The data in Experiment VII show a Q_{10} of 6.7 for the rate of increase of the cap diameter.

The storage atmosphere, which can be controlled to a certain extent by the storage container, can also affect the opening of the cap. If mushrooms are stored in a sealed container, and thus prevented from respiring, the result is retardation of the opening of the cap. The rate of opening will increase, within limits, as the ventilation in the container is increased. The usefulness of this phenomenon as a method of controlling opening has already been mentioned under "Transpiration."

The effect of gamma irradiation on the dimensional changes is impressive. An irradiation dose as low as 10 Krads has a profound effect on the parameters D.O. and O.R. The 10 Krad dose in Experiment VI gave a three-fold shelf life extension over the controls, as measured by the ratio of the increase in cap diameter or by D.O. Higher doses give a significantly greater retardation in cap opening (as high as five-fold), but not in proportion to additional dose. Above 50 to 100 Krads, the effect of added dose on the rate of cap opening is negligible. As a matter of fact, mushrooms treated with 100 Krads of gamma irradiation do not open appreciably under any condition. Therefore, it would seem unnecessary to give doses in excess of 100 Krads, thus increasing the cost of application.

The effect of temperature on the rate of cap opening of irradiated mushrooms is not as great as it is in those that have not been irradiated (Q_{10} about 3). Also, as was the case of unirradiated mushrooms, the rate of cap opening was affected by the container style in which the irradiated mushrooms were stored.

The effectiveness of irradiation in preventing stem elongation appears to be dose dependent. The data in Experiment VI show that doses of 10 and 20 Krads accelerate the rate of stem elongation. A dose of 50 Krads, however, did not affect the elongation rate, and 100 Krads significantly retarded the rate of stem elongation. Experiment VIII, on the other hand, suggests that 50 and 100 Krads increase the rate of stem elongation. The desiccation of the stems of the control samples in this experiment, however, probably negate this result. While Maxie et al. (1967) found no advantage at any dose (0 to 100 Krads) or any temperature (32, 41, or 48°F), Bramlage and Lipton reported a definite reduction in the stem elongation at the higher doses in this range. Consequently, the effect of irradiation dose on the elongation of mushroom stems, whether or not this change is important, is yet to be resolved.

A delay between harvest and irradiation causes a loss in some of the benefit of the irradiation dose based on the retardation of cap opening. It is obvious too, that any loss of quality occurring before irradiation cannot be regained by this treatment.

Application

Irradiation can be used to successfully extend the storage life of fresh cultured mushrooms by as much as five-fold as measured by the retardation of the most obvious change which occurs during storage, the opening of the cap (See Fig. IV). Irradiation also gives better retention of white color and may, at higher doses (100 Krads), retard elongation of the stem. The dose which is necessary to obtain the most benefit from irradiation appears to be between 100 and 200 Krads, but these doses are probably not the most practical doses for many marketing situations. It is the writer's opinion that the magnitude of the irradiation dose must be tailored to fit a given situation. Storage factors which are likely to influence the choice of dose are temperature, atmosphere, exposure to air blasts, relative humidity, severity of handling and bruising, the style of container, marketing time, and time between purchase and consumption. The irradiation treatment should be given as soon as possible after harvest.

The factor which will dictate whether irradiation at any dose will be successful as a means of extending the storage life of mushrooms is that of economics. The benefit derived from applying irradiation must more than offset the cost of applying this treatment. Studies investigating the cost of applying irradiation to mushrooms have not been

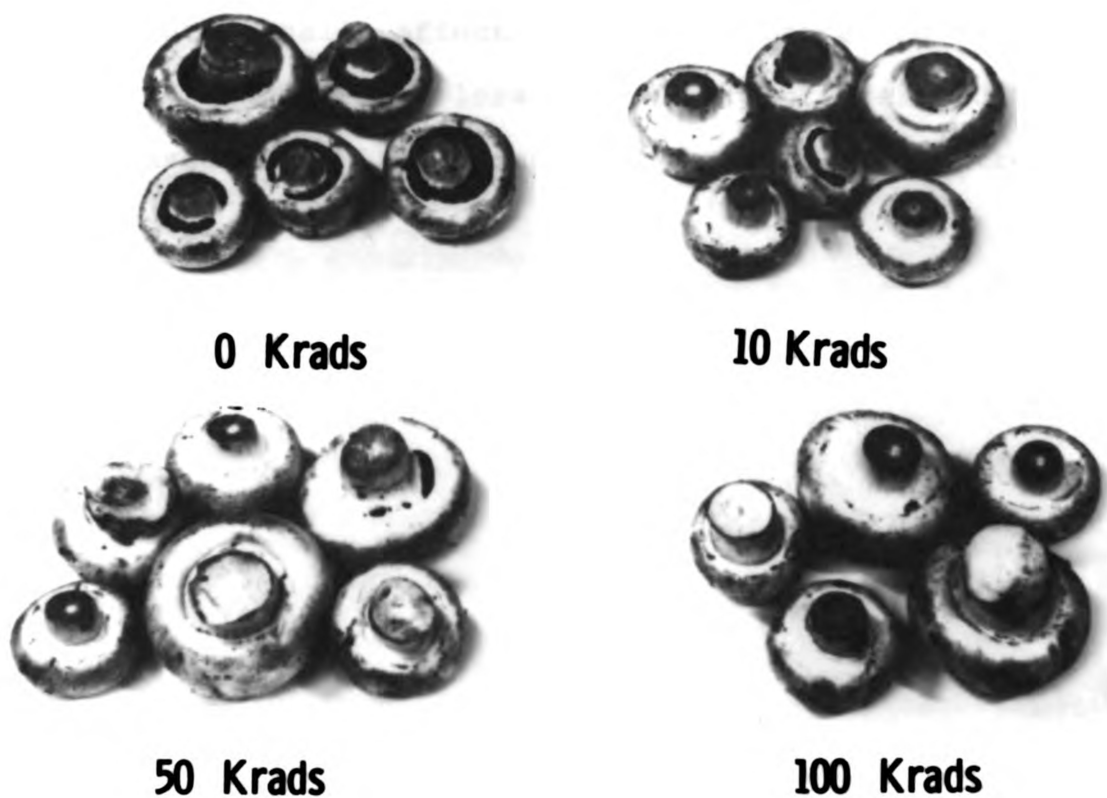


Fig. IV. The effect of irradiation on the extent of cap opening after seven days of storage at 10° C.

undertaken, but the relatively high selling price of mushrooms suggests that the additional cost of irradiation would not drastically affect the selling price and would probably be considerably less than the return derived by the increased shelf life induced by the irradiation treatment.

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APPENDIX A

Sources of Gamma Radiation

I. Phoenix Memorial Laboratory:

Prior to July 1967, all mushrooms were given gamma irradiation doses with the pool-type Co-60 source housed in the Phoenix Memorial Laboratory, University of Michigan, Ann Arbor, Michigan. The source strength was 8,500 to 9,000 Curies during the period in which these experiments (Experiments I through IV) were conducted. The dose rate at 50 cm from the source center was about 30 Krads per hour.

The source is composed of 12 source strips arranged in a circular pattern (radius about 8 cm). During irradiations, these strips were raised into a cylinder having an outside diameter of 26 cm and a height of 34 cm. The time required to raise the source from the bottom of the pool to the fully-up position was about 110 seconds. The pool depth is about 12 feet. The temperature of the cell and the corridor leading to the cell was controlled by a thermostat set at 8°C.

II. M.S.U. Food Science Gamma Facility:

Mushroom experiments performed after July, 1967, (Experiments V-VIII) were conducted using the pool-type Co-60 gamma source housed in the Food Science Building, Michigan State University, East Lansing, Michigan. The strength of this source was measured to be 51,500 Curies in May of 1967. The dose rate at 50 cm from the source center was measured to be about 200 Krads per hour.

The source is composed of 24 BNL Mk1 doubly encapsulated source strips arranged in a circular pattern and, when the source is in the fully-up position, are enclosed in a stainless safety shield having an outside diameter of 34.5 cm. The time required to raise the source from the bottom of the pool to the fully-up position was 19 to 21 seconds. The pool depth is 15 feet. The temperature of the cell and the corridor was ambient for all experiments (usually about 23°C).

Source Calibration

The dose rates at both Co-60 gamma facilities are based on the Fricke method of chemical dosimetry (ASTM, 1959). The Fricke dosimeter is generally accepted as a primary standard of radiation dose and is based on the linear conversion of ferrous ion to ferric ion by irradiation. This method has an upper limit of 40,000 rads total dose in aerated solutions and is essentially energy and dose rate independent and reasonably stable.

This method involves the measurement of the change in absorbance of a dosimetry solution (0.5 M in ferrous ammonium sulfate at 305 mμ, 0.5 mm slit width). The change in absorbance is attributed to the increased concentration of the ferric ion produced by the oxidation of the ferrous ion. The change in concentration is determined by comparison to a standard curve (the molar extinction coefficient is defined as the slope of the straight line formed by absorbance versus concentration in moles/liter) and the dose, in rads, is then calculated by:

$$D = \frac{(OD_i - OD_u) \times A \times K}{E \times P \times G}$$

Where:

D = dose in rads

OD_i = optical density (absorbance) of the irradiated solution

OD_u = optical density (absorbance) of the unirradiated solution

A = Avogadro's number = 6.023×10^{23}

K = Conversion factor from electron volts per kilogram to rads, $\text{ev/kg} = 1.602 \times 10^{-15}$

E = Molar extinction coefficient

P = density of the solution in grams per ml

G = number of molecules reacting per 100 electron volts absorbed = 15.6.

Test tubes made of borosilicate glass and containing dosimetry stock solution were placed at various positions

in the radiation cell. After irradiating the samples for a predetermined length of time, the absorbance of the solution was measured with a Beckman model D U spectrophotometer and, by the use of the preceding formula, the dose rates at these positions were calculated.

Dose rate measurements, made by the author, of the source housed in the Phoenix Memorial Laboratory, showed the dose to be about 10 percent higher than that reported by the facility. Therefore, it is possible that the dose received, when compared to doses given at M.S.U., is somewhat higher than reported in Experiments I through IV.

Method of Irradiation

Mushrooms contained in one-quart polyethylene tubs, in one-pint wooden boxes, or in commercial one-pound paper-board boxes were arranged in a circular pattern at a predetermined distance from the source center. The magnitude of the dose was dependent on the distance from the source center and the time of exposure. The desired dose levels could thus be applied by placing mushrooms at different distances (the dose rates at these distances were calculated from the dosimetry measurements previously described) and exposed to the irradiation for a specified time interval.

Due to the relatively low dose rate of the source housed in the Phoenix Memorial Laboratory, the samples usually had to be placed rather close to the centerwell.

Also, again due to limited available space, it was usually necessary to place the samples so that the mushrooms receiving the lower doses (the ones farther from the source center) were shielded considerably by the ones receiving higher doses, and sometimes it was even necessary to stack the containers two or three high in order to irradiate a large enough sample. Nevertheless, the reported dose was calculated on the basis of the dose rate, as determined by previous dosimetry, at the center of the container. All samples were rotated 180° at $1/2$ irradiation time in an attempt to minimize the dose differential within the containers.

The mushrooms in Experiments V through VIII were irradiated at the M.S.U. Food Science gamma facility in a similar manner, but more available space and much higher dose rates permitted placement so that the difference between calculated and received dose was probably much smaller. The samples were always placed so that shielding by higher doses was kept at a minimum; they were usually placed so that there was nothing between any sample and the source. Also, the higher source strength allowed the samples to be placed at a larger radius to receive the same dose rate so that more samples could be accommodated without stacking. The received dose was calculated as 87 percent of the dose (from dosimetry) at the face on which radiation is incident (the mushrooms were contained in the

polyethylene tubs for all irradiations at this facility). This figure (87 percent) is based on shielding measurements on cherries with an allowance for the lower density of mushrooms. All samples were, as at Ann Arbor, turned 180° at 1/2 irradiation time to maximize dose uniformity within the containers.

APPENDIX B

Agriculture Handbook No. 8 (Watt, 1963) gives the following composition for raw mushrooms, Agaricus bisporus:

Water	90.4%		
Protein	2.7%		
Fat	0.3%		
Carbohydrate	4.4%		
Fiber	0.8%		
Ash	0.9%		
Calcium	6	milligrams/100 grams	
Phosphorous	116	"	"
Iron	0.8	"	"
Sodium	15	"	"
Potassium	414	"	"
Thiamine	0.10	"	"
Riboflavin	0.46	"	"
Niacin	4.2	"	"
Ascorbic acid	3.0	"	"
Caloric value	28	calories/100 grams	
Vitamin A	Trace	amounts	

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