THE PRODUCTION OF FOG AS A THERAPEUTIC AGENT

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The use of fog as a therapeutic agent is an old science, but present-day methods of generation and control promise many new applications. In order to study the method of generation of fog, an understanding of the sources and types of moisture suspended in the atmosphere is necessary.

Humidity is water as it is found in the atmosphere. It exists in two basic states: (1) invisible vapor of low pressure steam, intimately and invisibly mixed with air; and (2) finely divided water droplets commonly referred to as "fog," existing in air which is supersaturated. These finely divided water droplets constitute the only visible form of humidity, and may be subclassified into two categories: (a) mists, which are very small air-borne droplets of materials that are ordinarily liquid at normal temperatures and pressures. Mists are formed by atomizing, by spraying, or by the escape of a dissolved gas, upon release of pressure. And (b) fog, which is limited by definition in most classifications to those air-borne droplets formed by condensation from the vapor state. The distinction between mists and fog is important because violent action is usually necessary to create a mist of very small droplet size from a liquid, whereas fogs are created from the vapor state at extremely small particle size.

All of these droplets are constantly in a state of transition, either becoming larger through agglomeration as the vapor is cooled, or becoming submicroscopic in size and eventually reaching the vapor phase as the droplets are warmed. Variation in pressure as well as in temperature may cause these transitions, but this discussion is limited to changes occurring at one atmosphere of pressure.

"RELATIVE HUMIDITY" AND "ABSOLUTE HUMIDITY"

The term "relative humidity" is employed to express the amount of moisture actually existing in air as compared to the amount of moisture necessary to fully saturate the same air. However, the term lacks scientific exactness, inasmuch as the relative humidity of air will vary with changes of both temperature and pressure. "Absolute humidity" is therefore a preferable term for moisture content, since it describes the given weight of water contained in a unit volume of

This paper was presented before a meeting of The Academy of Anesthesiology held in Hartford Hospital, in Hartford, Connecticut, October 29, 1955, and accepted for publication February 14, 1956. Mr. Arnold is Engineer, Melchor, Armstrong, Desso Company, Inc., Ridgefield, New Jersey. Dr. Tovell is Chairman of the Department of Anesthesiology of Hartford Hospital.

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air. Absolute humidity is expressed as the number of grains by weight of water per pound of dry air, and is thus a figure which can remain constant despite variations in the temperature or pressure of the air. A grain of moisture, incidentally, may be defined as a weight equal to 1/7,000th of a pound of water; and a pound of dry air has a specific volume of 13.33 cubic feet.

Hygrometers

Many types of hygrometers are available for measuring the amount of water entrained in the air below saturation point. One of the most commonly used, and most accurate, of these is a psychrometer. This type of hygrometer consists of two mercury thermometers, one of which has a wick or sock applied to its bulb. The wick is wetted with water prior to use and ventilated with air moving at a minimum rate of 900 feet per minute. Due to evaporation of the water on the wet bulb, this thermometer will indicate wet bulb temperature, a lower temperature than dry bulb temperature, the difference being known as the "wet bulb depression." Charts and tables are available showing the relation between wet bulb depression and the specific humidity (1, 2).

Great care must be taken, however, not to rely upon dry and wet bulb thermometers unless a substantial velocity of air is passing over these instruments. Such instruments have been used in the past in incubators containing relatively still air and have produced falsely high indications of relative humidity. An observed wet bulb depression of 4 degrees in 77 degrees Fahrenheit still air falsely indicates a relative humidity of 82 per cent or 116 grains per pound of dry air; whereas if the wet bulb is placed in a high velocity air stream of the same atmosphere, a 9 degree F. wet bulb depression is observed, indicating the actual relative humidity of 63 per cent, or 88 grains of moisture per pound of dry air. Thus if there is room in the incubator to insert one hand with a sling psychrometer, it is possible to get a much more accurate reading of relative humidity by whirling the thermometers rapidly about in the air to produce the effect of a rapid stream of air over the wet bulb. Another method of measuring humidity is the dew point hygrometer, which employs a metal mirror and a means of controlling the temperature of this metal mirror so that the temperature may be read at the dew point of the air; that is, that temperature at which the air becomes saturated and moisture begins to condense on the mirror.

Hygrometers are commonly used with human hair or with animal membrane as an element. An indicator or pen moves across a dial as the human hair changes in length due to a change in humidity. These instruments become valueless as one approaches the saturation point, since a drop of water condensed on the hair will cause a false
high reading. There are other instruments to measure humidity which use the electrical resistance of a salt film, which varies with the humidity of the atmosphere. These also fail once saturation is reached. A more accurate but slower method of measuring the humidity of any atmosphere is by extracting and weighing the water vapor from a known sample. Powerful desiccants such as silica gel or calcium chloride can be used for this purpose. Freezing the water vapor out of the measured stream of air or gas with solid carbon dioxide and weighing the resulting ice is a similar technique. These latter methods require first the extraction of the known sample from the atmosphere. Thermal conductivity cells, employing a Wheatstone bridge, may be used to measure extremely low humidities, but these become inaccurate as the relative humidity increases. Dry and wet bulb thermometers are probably the most satisfactory devices for use in measurements of subsaturated vapor up to 98 per cent relative humidity.

Instrumentation for indicating and recording humidity is limited commercially to the subsaturated range. There is as yet no practical commercially-produced instrument for measuring supersaturated atmospheres. In the laboratory, the weight of moisture in supersaturated air may be measured by the chemical absorption method or by freezing the moisture out as ice. In a high humidity room it is possible to pass the air over the air conditioning coil for a fixed time, and by thus dehydrating it to measure the water volume removed; or by heating a sample of the room atmosphere above the dew point temperature, and thus permitting the air to absorb all the water into vapor state, to use dry and wet bulb psychrometers to measure the water vapor content. This last method will soon be made practical by the development of a device which will so process a small continuous sample from an incubator, or high humidity tent or room.

The Psychrometric Chart

The psychrometric chart (fig. 1) is a graphic depiction of the moisture content of air at varying wet and dry bulb temperatures, and relative and absolute humidities at the standard atmospheric pressure of 29.97 inches (or 760 millimeters of mercury) (2). An increase in atmospheric pressure will reduce the ability of air to hold water—much like the squeezing of a sponge—but, for most considerations in the field of air conditioning, changes of atmospheric pressure of less than 1 inch of mercury may be disregarded. The abscissa or bottom horizontal line (fig. 1) represents the dry bulb temperatures as obtained by reading any standard thermometer. The saturation curve is marked off in wet bulb temperatures, and this line represents saturated air conditions, or the condition when air can hold no more water in the vapor state. To the right of this line is the clear or unsaturated area; to the left is the fogged, or supersaturated area. The moisture content of air can be computed with equal ease on either side of this saturation
line. The right hand side of the graph is marked off as the water content in the air in terms of grains (weight) of moisture per pound of dry air. These readings give the "specific humidity," or the total amount of moisture actually in the air. The curved lines paralleling the saturation curve are called "per cent relative humidity lines" and normally represent the 90–80–70–60–50–40—and so on percentage relative humidity. It should be noted that a great many different conditions of air may exist at a given relative humidity. Furthermore, it

![Psychrometric chart](http://anesthesiology.pubs.asahq.org/pdfaccess.ashx?url=/data/journals/jasa/931829/)

**Fig. 1.** Psychrometric chart.

can be seen from the psychrometric chart that, while at 70 °F, a saturated atmosphere will hold 111 grains of moisture per pound of dry air, at body temperature this moisture content would represent only 40 per cent relative humidity, since it would require 290 grains of moisture per pound of dry air to produce saturation at that temperature.

A point on the chart (point no. 1) may be assumed at 65 °F, dry bulb and 40 per cent relative humidity, representing 36.5 grains of moisture per pound of dry air, 52 °F, wet bulb temperature, and a 40 °F, dew point temperature. A second point on the chart (point no.
may be assumed at 80 F. dry bulb and a relative humidity of 80 per cent representing 123.5 grains of moisture per pound of dry air, 75 F. wet bulb temperature, and a dew point of 73 F. This is to say, if the air were cooled to this temperature, 73 F., moisture would begin to condense out. Now, if an equal volume (1 cubic foot) of each of the above air samples is combined, the two quantities of air at different conditions will form a third condition, which may be shown on the graph to lie at the midpoint (point no. 3) along a line between the two initial conditions (point no. 1 and point no. 2), and will represent 2 cubic feet of air at dry bulb 73 F., wet bulb 65 F., dew point 61 F., relative humidity 68 per cent, and a moisture content of 80 grains of moisture per pound of dry air. On the other hand, if unequal volumes of air of differing conditions are combined, the conditions of the combined sample of air will vary accordingly. Thus if 3 volumes of air at the conditions of point no. 1 are combined with 2 volumes of air at the conditions of point no. 2, there will result 5 volumes of air with conditions represented by point no. 4 on the graph, two fifths of the distance between points 1 and 2. This air would be at 71 F. dry bulb, 62 F. wet bulb, 57 F. dew point, 61 per cent relative humidity, and would contain 70 grains of moisture per pound of dry air (2, 3).

It should be noted that by adding heat to a given air condition, the dry bulb temperature is raised without any concomitant change in the moisture content. Similarly, moisture can be removed or added without affecting any change of the dry bulb temperature. Finally, air may be made more saturated by removing heat from it.

**Droplet Size**

If the moisture vapor entrained in air is not sufficient to saturate it, it will be invisible. There can be almost perfect visibility at 100 per cent saturation when all the water has flashed into saturated vapor (2). This is usually a fluctuating condition, however, for if the temperature is lowered even 1 degree, the saturated vapor will become supersaturated and will (4) create water droplets which will be visible, if not in strong daylight at least in darkness when the beam of a flash light is reflected on them. When air is supersaturated, there can be various ranges of visibility in direct proportion to the weight of water per pound of dry air. Therefore if the ultimate in available moisture content is desired, visibility will necessarily be poor.

It is desirable to know the size of the droplets which exist in supersaturated air. The measure of fog particles is the micron, which is a droplet size equal to 1/1,000th of a millimeter in diameter. According to the charts developed by Frank (4), visible fog may contain droplets from a fraction of a micron to 40 microns in size, and mist may be entrained in atmosphere with particles up to 100 microns in diameter. The measurement of particle sizes of water vapor is extremely difficult. Nebulized sprays lack uniform droplet size and are a mixture of heavy
and light particles from 100 microns down to less than 1 micron in size. The heavier particles, above 10 microns, are continuously breaking up into fine particles because of air friction, or dropping out of the atmosphere due to their own weight. The droplets from 10 microns down tend for a short time to remain suspended. Unless recirculated, they will fall out in a matter of moments in the form of condensation. The smaller droplets, when sprayed from a nebulizer, tend to agglomerate and become larger droplets. Since there is no static condition, it is difficult to obtain slides or other records of droplet size. Some measurements have been obtained by atomizing suspensions of silver iodide (5) and examining the dry suspension with an optical microscope. Electrostatic precipitators also have been used successfully by Bourne and Fosdick (6) to measure particle size of air-borne dust. Some work on determination of particle size has been done by Leary (7) using radioactive aerosols. He utilized the radio-autograph, using alpha-emitting compound, collecting the active material on filter paper, and placing them in contact with nuclear track plates for various exposure times; by counting the number of tracks in the emulsion for given exposure time the size of each emitting particle could be calculated.

The research of Abramson (8), Siegel (9), Bryson (10), and others (11) has contributed to our general understanding of particle size in aerosol therapy. It appears that particles 30 microns in diameter or larger are baffled out in the trachea; those 10 to 30 microns reach the terminal bronchioles; those 3 to 10 microns in size stop in the alveolar ducts; and those 0.5 to 3 microns in diameter penetrate into the air sacs themselves. Particles smaller than 0.5 micron enter the air sacs but, because of their extreme lightness, approximately half of these are expired at once. Talbot, Quimbly, and Barach (12) employed radioactive sodium to demonstrate that from 63 to 96 per cent of particles 0.8 to 6 microns in radius (with mean average radius of 1 to 3 microns) will be retained. The indications from these studies are that droplet sizes under 10 microns, and down to 0.5 micron, are therapeutically desirable.

**Nebulization**

In studying the ability of air to retain and absorb moisture it became apparent that use of nebulizers to create fine droplets was inherently unsatisfactory because of the natural tendency for water to agglomerate, the fact that in nebulization only a portion of the particles become small enough to be usable, and the fact that a large portion of the particles are too heavy to be entrained or else rapidly agglomerate into particles too heavy to be entrained.

One of the more satisfactory methods of nebulizing fine droplets was found to be by the use of a bent capillary tube (fig. 2), the center of which is attached to an oxygen supply tube drilled with a small hole
on the nozzle side, with a large hole on the opposite side of the capillary tube. A venturi effect is created by the velocity of the gas passing from the small hole, across the capillary, and out of the large hole, drawing water up both legs of the capillary tube. This water is broken into fine droplets by velocity and friction. Many other recent advances have been made in the nebulization of various drugs and liquids, using compressed gases and pumps as propelling agents. Wetting agents have been used to reduce surface tension of the droplets, thus permitting the production of finer particles, but with the mechanical disadvantage of having a tendency to gum up fine ports in the nebulizers.

Although relatively inexpensive, nebulizers have several inherent drawbacks. They operate normally with cold water, which tends to reduce the capacity of the atmosphere for absorption of water vapor;
they are not equipped with a return system, and therefore the heavy droplets finally agglomerate and fall out in the form of free water on the bed clothes or on the floor; they produce non-uniform droplet sizes, so that a large percentage of the water dispersed is rendered ineffective; and they require the use of either compressed gases or the use of a pressure pump. If oxygen is used, control of its concentration in a safe range for the newborn infant (13) in an incubator is a problem necessitating use of flowmeters compensated for back pressure and nebulizers equipped with a venturi to introduce sufficient air to reduce the concentration of oxygen to 40 per cent or under.

Some of these problems have been overcome in part, but they demonstrate the need for humidifiers of a more advanced type. The spinning disc type humidifier is one of these. In this type of unit, a high speed disc slings particles of water centrifugally from its periphery to shatter against fine mesh screens, which serve to reduce particle size further and create a fine fog which is fairly effective until equilibrium is reached. The advantages of this system are that the heavy particles are partially eliminated by the screen and that no oxygen is required as a propellant. The spinning disc type humidifier, however, like the nebulizer, possesses the disadvantage of producing droplets mechanically which are subject to condensation as equilibrium is reached. Furthermore, as with a nebulizer, the evaporation of the particles causes a reduction in the temperature of the atmosphere which passes through the humidifier; this is an additional handicap, since the air at this lower temperature cannot absorb or carry as much moisture as warm air could carry. However, recent models of the spinning disc type humidifier have been designed for use with oxygen tents and have proved effective in raising the relative humidity within such tents.

High Humidity Oxygen Tent

One development in the effort to make high humidity therapy more satisfactory has been the high humidity oxygen tent (fig. 3). This device was designed in cooperation with the late Dr. Francis F. Schwentker, of Johns Hopkins Hospital (14), in an attempt to provide a higher moisture content at controlled temperatures to the far reaches of the lung. This unit uses the spinning disc type of humidifier because of its advantage over the nebulizer, in that it delivers a great deal more moisture per hour into the atmosphere. However, in the incorporation of the spinning disc type humidifier into the oxygen tent, consideration was given to the shortcomings of this device and steps were taken to offset these. The water supply is heated to raise the ability of the water to break into fine droplets, and, by heat exchange with the atmosphere, to increase the temperature of the air to permit greater absorption. The return air from the tent canopy is split into two streams after it is drawn into the upper section of the cooling
duct. One pressurized stream follows the normal course of the oxygenated air through the cooling coil where it is cooled to approximately 60 to 65 °F., and then returned in the saturated state to the upper part of the oxygen tent canopy. The other stream of air under pressure passes with maximum velocity over the heated water and through the spinning disc of the humidifier until it reaches a temperature of 85 to 90. This supersaturated atmosphere at high temperature then passes through a corrugated duct where many heavy particles are trapped out on the convolutions, and then through a settling chamber where, by gravity, additional heavy particles fall out due to the reduction in velocity. This warmed supersaturated stream then passes to the top of the canopy, where the stream blends with the cool air at 60 to 65 °F. from the Freon cooling coil. The mixing of these two streams of saturated cool and supersaturated warm atmosphere creates a fog when the two strata of air of different temperatures and moisture content blend (fig. 1). This fog circulates through the canopy and is

**Fig. 3. High humidity oxygen tent.**
removed and replaced every thirty seconds, before it can reach equilibrium. It is then passed through the cooling coil of the oxygen tent, where it is condensed.

The precipitation of the moisture from the air twice a minute by the cooling coil will effectively remove large dust particles, which may reduce the concentration of micro-organisms which tend to become suspended on air-borne particles. The condensate containing the washed-out waste matter from patient exhalations, entrained dust and other foreign particles, is then drained into a waste receptacle outside of the oxygenated atmosphere. By keeping the atmosphere clear of dust and in constant circulation at the rate of 2 air changes per minute, it has been possible to continue to suspend and remove the droplets before they agglomerate and precipitate. This ensures the delivery of only fine particles to the patient’s airway, and at the same time prevents rain soaking the bed clothing.

The spinning disc humidifier in the high humidity tent is designed to throw 1.5 pints, or 11,000 grains of water per hour into the atmosphere. In actual operation, nearly 1.25 pints may be re-collected from the condensate drawer of the cooling coil. The unmeasurable difference represents the quantity that unavoidably is trapped out into the bed clothes. The weight of water circulated per hour, divided by the number of pounds of air recirculated within the canopy per hour, represents the number of grains of moisture per pound of dry air present in the atmosphere for the patient to inhale.

**Steam Humidification**

The oldest means of increasing the moisture content of air is by the release of steam from a steam kettle directly in the patient area. This steam initially has the advantage of having uniformly minute particle size as it issues from a pipe in which its temperature is high. It is released in nearly as true a vapor state as is possible to attain with this method. The apparatus has the disadvantage of increasing the temperature of the room, which although beneficial from the standpoint of increasing the ability of the atmosphere to absorb moisture, also raises the metabolism of the patient above normal and in addition removes the patient from the theoretical comfort zone. As the steam particles fall, like those particles thrown from the nebulizers and spinning discs, they agglomerate as equilibrium is reached, wetting the floor and bedding and causing extremely difficult conditions of nursing care.

**The Natural Fog Generator**

A natural fog generator has been developed to create, in a full-sized patient room, conditions of humidity previously only approached within the high humidity tent canopy (fig. 4). In this unit steam has been harnessed in a new and different way by cooling, blending, and injecting
it into the room atmosphere in such a manner that the objectionable heat is either removed or used to control room temperature as desired. The resultant superfine particles of moisture are recirculated at the rate of one air change per minute before being swept from the room and precipitated by the cooling coil. There is not time for agglomeration and subsequent precipitation to take place within the room, and the droplets remain in the range of therapeutically-useful particle size. The fog generator eliminates the need for enclosing a patient in a canopy, thus lessening the tendency toward claustrophobia and permitting nursing care without interruption of therapy.

The refrigerant circuit consists of an oversize copper coil with closely spaced aluminium fins. As Freon-12 circulates through this coil, controlled by a multi-outlet expansion valve, it changes state from a liquid under pressure to a gas at 34 °F, and therefore absorbs the latent heat of evaporation. This reduces the return air temperature to 50 °F, and condenses its entrained moisture, so that large droplets are prevented from recirculating. The Freon then returns to the motor compressor, where the heat of compression is added to it, and is pumped into the “tube in tube” condenser where the Freon gives up its heat to the cooling water in the adjacent tube and condenses to a liquid state before returning to the cooling coil.
The cooled return air, saturated to 100 per cent relative humidity at 50°F, discharges into the room through a plenum, where it mixes intimately with live steam at approximately 10 pounds pressure, supplied through a dead-end pressure reducing valve. The resultant temperature is manually set, but is automatically controlled by a volume of steam used to balance the cooling capacity of the coil. Heavy particles formed by the mixing air stream are drained away, and the remaining fine droplets are blended with the room atmosphere to create a fog of the required density.

The creation of a natural fog leads to an air conditioning situation depicted on the psychrometric chart (fig. 1) that is to the left of the saturation curve, beyond 100 per cent relative humidity, with enough moisture to maintain the air in the fogged state. This state is an unstable one in as much as the excess moisture present tends to settle out if the air motion is not maintained and will condense out on all surfaces at or below the saturation temperature of the air. At 1 micron, water particles settle at the rate of 5 inches per hour in still air and at 5 microns, 1.5 inches per minute in still air (4). At 10 microns, 7 inches per minute is the settling rate. One air change per minute is sufficient to keep these particles entrained and the ceiling, walls and floor dry.

**The Psychrometry of Natural Fog**

The psychrometry of the air from a Natural Fog Generator is important. The air within the room is circulated so that there is a complete changeover once each minute. The air in the evaporator coil is cooled to 50°F. and delivered in a saturated state (fig. 1, point no. 5) containing 53 grains of moisture per pound of dry air in sufficient quantities to cool the room to 68°F. in the upper mixing chamber. Live sterile steam at 212°F. is added in amounts necessary to reheat the room to 75°F. In so doing the room moisture content reaches 166 grains of moisture per pound of dry air, as represented by point no. 6, which is the intersection of the 75°F. wet bulb line extended into the fogged field and the chart ratio angle line for 212 steam, extended from the saturation curve at 50°F. While in actuality point no. 6 is mathematically possible under conditions of no heat gain or loss, in reality heat loss from or influx into the room, plus air leakage, causes a slightly different end-point than point no. 6. This point represents a dry bulb temperature of 75°F., and a wet bulb temperature of 75°F. A dense fog exists within the room which has a total moisture content of 166 grains per pound of dry air, 132 grains of which are in vapor state in the air and 34 grains (or 25 per cent of 132 grains) of which are in suspension in the air in the form of fog. The atmosphere may be said to be 25 per cent supersaturated.

This figure of 25 per cent supersaturation is higher than the normally expected average fog production because of various influencing
factors of heat gain: 10 per cent excess moisture seems to be about the average obtained, although percentages as high as 36 per cent have been found. Furthermore, there are limiting factors as to the concentration of fog that may be desirable, the denser the fog, the greater the decrease in visibility to the point at which the nursing personnel cannot see the patient. The limit of visibility has been reached for all practical purposes at a 10 per cent supersaturation in the temperature range of 70 to 75 F. Control of visibility is obtained with the use of a reheat coil.

**Humidification Within the Pulmonary Tree**

A final and important consideration of the Natural Fog Generator must be the amount of humidification it can produce within the bronchi and alveolae. A great deal is yet to be learned about the behavior of water vapor and water particles in the segments of the pulmonary tree, but certain theoretical effects can be estimated. One pound (or about 14 cubic feet) of normal room air at 75 F. may normally contain 50 per cent relative humidity or 66 grains of moisture. Inhalation of this normal atmosphere through a tracheotomy tube or through nasal passages congested with mucus into a congested bronchial tree will both warm this atmosphere toward body temperature and increase its affinity for moisture. If it reaches body temperature, 66 grains of moisture per pound of dry air represents only 24 per cent relative humidity. It therefore can theoretically absorb moisture from the mucous secretions and the atmosphere of the bronchial tree until it is exhaled at close to saturation and almost at body temperature, having thickened the mucus and internally dehydrated the patient by the removal of some portion of the 224 grains of moisture required to saturate each pound of air inhaled.

One pound of room air at 75 F., if supersaturated to contain 166 grains of moisture (equivalent to saturation at 82 F.), would if allowed to reach equilibrium in the lungs have a 58 per cent relative humidity at body temperature and would only require 124 grains of moisture to become saturated. It is probable, however, that equilibrium and the subsequent true vapor state of such a mixture is never reached. Although free droplets probably do reduce in particle size as they warm and partially flash into vapor, many of these particles are actually deposited by contact on the mucous membranes and thus saturate and soften the mucous secretions, until they are fluid, allowing a sub-saturated atmosphere to be exhaled without having necessarily reached saturation or body temperature. Herein lies the clinical utility of fog as a therapeutic tool.

It was on this basis that a fog generator was installed and has been in operation at Hartford Hospital since February, 1955. Preliminary experience in the treatment of tracheobronchitis, tracheal edema following removal of foreign bodies, and emphysema has been encourag-
ing. The treatment of patients suffering from poliomyelitis and requiring a tracheotomy during maintenance in an iron lung has been particularly satisfactory. When sufficient data have been accumulated, they will be submitted for publication.

ACKNOWLEDGMENT

All the charts illustrating this article were drafted by W. J. Clement, Jr.

REFERENCES

2. Goodman, William: Air Conditioning Analysis, New York, The Macmillan Co., 1947, Chapter 1-5, 6; 4-1,14; 5-1,4; 5-1,4.