Definitions.

Cotton – a plant, which is growing in wild in some countries like Mexico, India, Australia. A plant’s fruit is so called “cotton boll”, which contains the seeds surrounded by fibers which are growing at their surface. When mature, the boll walls are drying and opening. Cotton is being cultivated in many countries. During the harvesting season the seeds together with fibers are mechanically taken out of the bolls, collected and delivered to the “Gins”.

Gin - cotton processing factory which is providing primary processing of cotton, which includes separation of fiber and seeds and their cleaning. Cotton fibre is then packed into “bales” (of 170 – 240 Kgs of weight) by pressing them at high pressure and wrapping with plastic straps and fabric or plastic.

Seed cotton – cotton plant seeds together with fibers on their surface. Normally about 42-50% of seed cotton weight is comprised by the fibrous component. This component is also subdivided into fractions. Main fractions are spinnable fiber (lint) and linters.

Cotton fibre (lint) – natural fiber, like wool, but consisting mainly of cellulose, which is growing on the surface of cotton plant seeds. The mass of lint is obtained during the normal process of ginning and has the staple length of 25 – 50 mm. Its proportion is about 25 – 42% of the seed cotton weight. Lint is used mainly to produce yarns (at the spinning mills) and then - fabric at textile factories.

Linters - It is short fiber with the length of 5-20 mm which can’t be used for producing fabric. Its proportion is about 8 – 12% of the seed cotton weight. Linters is used mainly to produce cellulose, high quality paper (including paper to print banknotes) and some other chemicals. Linters is mainly obtained from seed cotton in Central Asia. Some other countries (USA, Australia, etc...) are not producing linters.

Cotton seeds – seeds of cotton fruit released from fibers. They are mainly used to produce edible cotton seed oil, and at the further stages – various chemicals and forage for cattle.

Humidity – regain value, or “Mass relationship of moisture” as per definition adopted in the CIS. It means amount of water in product divided by the dry weight of the sample, expressed in %. It is indicated as “W” in the spreadsheets and formulas.

Accuracy – deviation of obtained results from average results determined by means of the standard method in the trusted interval of 95% (i.e. 95% of results should fall into this interval). Accuracy is expressed herewith in the % of absolute humidity.

Spinning mills and textile factories need to know the humidity of lint in order to process it correctly. Many measuring devices were created for measuring of humidity of various textile fibers, including cotton lint. Technically the measurement of fiber humidity is not a difficult problem. Usually fiber sample is placed in the drying chamber and subjected to the effect of the air, heated by electrical heaters. In order to speed up the process, hot air flow may be pushed through the sample. But to the certain extent results are dependent on operators’ skills, as operator may prepare not enough uniform sample, measure its weight not precisely and so on. In order to avoid it, the semi-automated devices were created. They maintain stable temperature, stable air flow, automatic weighing of the sample, auto-calculation of the results and so on. As a result, the problem of humidity measurement of textile fibers may be regarded as solved. Provided results are precise enough.

In some countries, for example, in Central Asia, cotton industry need to measure humidity of seed cotton, i.e. non-processed mix of fiber and seeds. During procurement of cotton at the harvesting period, big volumes of seed cotton are arriving daily to the procurement centers. They need to be checked for humidity for technological and financial reasons. As cotton flow is very intensive, the time for each individual measurement is strictly limited. The target time is 5 minutes. Maximum what can be accepted by the industry, is 10-15 minutes. Besides this, accuracy of the measurement must be high enough, as with the existing cotton volumes each part of the percent of humidity means big money for either one or another party (seller or buyer). Maximum accuracy can be achieved using direct method of measurement, i.e. drying of seed cotton sample until completely dried state and comparing its weights before and after drying. Measurement of seed cotton humidity is technically more difficult than of lint humidity, as seed cotton consists of three main components - seeds, having complex structure, fiber and trash. These components have their own path of drying which is very different from each other. Main principles of measurement are the same as for the lint. Sample is being placed in the drying chamber and dried by the hot air. While lint is drying in few minutes, the seeds require 1.5 – 4 hours to be dried, dependent of concrete method used. So, the whole sample needs to be dried long time, meaning that direct method is
not applicable for industrial use for seed cotton. There are also some methods of rapid drying, when the sample is squeezed between two hot plates for about 5 minutes. This method is being widely used in Central Asia. But the shortcoming of this method is that the size of the sample is too small (40 grams), to represent the characteristics of the whole lot, and besides this, this method doesn’t have enough potential to be automated, which also reduces its applicability for industrial use. As cotton industry needs the rapid and reliable method of determination of seed cotton humidity, the decision was made to test the existing devices used to measure lint humidity, and to check their potential applicability for seed cotton. In order to find the most suitable device, the Internet search was undertaken along with traditional sourcing of available information. Results of this search brought to the conclusion that the best possible device is “Branca Regain Tester 70/5” (BRT) produced by the Italian company Branca Idealair di Branca Barbara S.A.S.” (see attachment No 1). This device has high accuracy when used for cotton lint measurements. It has high degree of automation and sufficient sample mass (up to 500 grams for cotton lint; up to 2 Kgs of seed cotton may be placed in it). Above all, this device is using the method of underpressure measurement which provides the higher speed of the tests compared to traditional methods. The appeal was sent to this company with the request to present one unit of this device at the disposal of the Science Research Center of Cotton Industry (Paxtasanoat) for carrying out of tests aimed to determine whether this equipment can be used for seed cotton humidity measurement. Producer agreed to present regain tester for the period needed for testing it. Equipment was delivered to Paxtasanoat Research Center and installed at its premises. The program of the tests was worked out, and the first series of tests were carried out. Description of the results is given here below.

I. Moisture distribution in the seed cotton.

As mentioned above, seed cotton has inhomogeneous structure. Moisture is contained in each of its components: fiber, seeds and trash. Fiber (or lint) is drying under heating conditions first of all. As it dries fast, it is not restricting the device’s performance. Trash is supposedly drying fast too, as it mainly consists of thin parts of leaves, which are losing the moisture fast enough simultaneously with lint, so not restricting drying performance too. The most time consuming part is represented by seeds. They have complex structure which can be simplistically described as relatively small (5-10 mm) ellipsoidal box/camera formed by woody peel, containing the seed kernel. Both peel and kernel contain some amount of moisture, which has different mechanism of accumulation. Seed peel may be considered as capillary accumulator of moisture, while kernel has colloidal nature (we consider only mechanical properties of seeds and avoiding their biological structure). When subjected to heating, the peel supposedly loses its moisture relatively fast; at later stage (after being heated enough) the kernel starts extraction of its moisture too. This moisture penetrates the capillary system of the peel and moves out of seed. This is just simplified explanation of the seed drying mechanism.

II. Preparation of Samples and General Provisions of tests.

About 100 samples of seed cotton were prepared for the tests. At the first stage of researches it was decided to use any samples without separation by seed variety, grade, lint content, microrai (thickness or fineness) and so on. The aim of the first stage was to estimate in general sense whether it is possible to work out the algorithm of measurement of seed cotton humidity by this device. Each of the samples was humidified by spraying of individual amounts of water into them and uniform mixing during spraying. Samples were then placed into plastic bags, sealed and kept for 3 – 5 days. During this storage the samples were being opened and thoroughly mixed twice a day. These conditions provided penetration of water into the structure of seed cotton. As the amount of sprayed water was different, humidity of samples was varying in the wide range, which was required for the tests. Similar technology was used to prepare the samples of lint and of cotton seeds. Ready samples of seed cotton were split into three parts to be tested by three different methods:

- 8x10 grams for testing by standard method in the drying chamber with minor air flow at the temperature of 110°C. The seeds contained in the samples must be preliminary crashed by special mechanical device. This method is used as etalon for the calibration of all other methods. It is
supposed to provide the accuracy of 0.5% of absolute humidity, which is the main criteria for all newly developed devices.

- 2x40 grams for testing by rapid tester using the method of squeezing the sample between two hot plates at the temperature of 195°C. This is the main rapid device used by the cotton industry of Central Asia.

- 1x600 grams for testing at BRT.

In order to provide enough accuracy of standard method, 8 samples by 10 grams of seed cotton each were being dried in the drying chamber for each test, and the average result of humidity was used for future comparison and calibration of BRT. Standard tests were carried out by the Research Center staff. Their results were used for comparison with the BRT test results. Even under these conditions, the 0.5% of individual standard test accuracy was not always achieved. Maximum deviation of these results was sometimes exceeding 1.5%. As we know that technical parameters of the drying chamber provide high accuracy, such deviations are due to non-uniformity of moisture distribution in the samples. This deviation was further taken into consideration while calculating the accuracy of BRT. Nevertheless, as for the further calculations only the average standard results were used, we may regard them as more or less accurate. Deviation of the average result is \( \sqrt[\ell]{n} \) of the number of repetitions less than of individual test, meaning \( \sqrt[\ell]{8} = 2.8 \), i.e. 2.8 times less, which is acceptable for the first stage of tests.

Results obtained by the rapid tester, were used just for reference, in case standard results were regarded as not matching the expectations.

Test at BRT were being carried out in one repetition only, as in the industrial way of using of BRT it will work the same way. Besides this, high sample weight was supposedly providing enough accuracy of BRT individual tests.

Each test on BRT was carried out until the difference between two consequent measurements was reaching 0.01% humidity. This is more strict than usually used in similar devices, but this criteria was applied deliberately as the target was to achieve the maximum drying level for further calculation of needed algorithm.

Following parameters were established for the tests:

- Hot air temperature - 125°C. Lower limit was supposed to be as high as possible in order to provide maximum drying efficiency; upper limit was determined by the condition of non-burning the fiber. 125°C was matching both conditions.

- Sample mass was taken at 600 grams. Few preliminary tests (not included herewith) showed that further increasing of the mass is not bringing to sufficiently better accuracy; reduction of the mass was worsening the sample presentability.

- After doing several preliminary tests (not included herewith) the following cycle was accepted: crying for 4 minutes followed by weighing. Main criteria was to dry the fibrous part of a sample curing the first cycle (this fact was determined at preliminary tests), then dry the main part of the seed peel during the next one or two cycles, then dry the seed kernel during the all next cycles. All results were stored in the PC and used for further elaboration of the algorithm of calculations.

III. Preliminary tests.

1. Prior to the seed cotton tests, preliminary tests were carried out for the lint and cotton seeds. Results are not given herewith, as they were used only for establishing of proper test conditions for the seed cotton, and not used for further calculations. Samples were split into two parts - to be dried with standard method (drying chamber) for determination of exact humidity, and with BRT tester. Uzbek rapid tester was not used, as measuring of lint is not a complex matter, and usually it is not causing any difficulties, so no need for additional measurements. Tests showed that complete drying of lint in BRT takes 3 - 5 minutes, dependent on initial humidity. This is fast enough, so there was no need for more
detailed breakdown of this process. Decision was made to use the average time needed for
drying of lint, as a criteria for the further drying cycles.
Drying of bald (naked, or delinted) seeds was requiring about 1.5 hours.

IV. Preliminary results.
Complete drying of samples was taking 2 – 4 hours dependent on their initial humidity, meaning that this
time is required for exact measurement of humidity. This time is of course, not acceptable for industrial
devices, being too long. Maximum what may be accepted by industry is 15 minutes, if not less And the
accuracy of measurement should be
The fibrous part was drying in 3-5 minutes, and drying of seeds was taking all the rest time. Entire time was
exceeding the sum of times of lint and seeds when dried individually during preliminary tests; we may
suppose that one of the reasons is that moisture evaporation at the spots of contact of individual fibers and
seed surface ("point of growth") is slower than at the clean surface of seeds.
Weight measurement was carried out each 4 minutes. About 32 – 50 cycles of 4-minute drying were
required for entire drying process. Results of individual weighing were used to create the "Drying curves" –
graphs reflecting the dependence of sample weight (and current individual humidity reading) from the
number of cycles or the time of drying (see pic.1). These graphs showed that drying curves have almost the
same shape for all samples. But the height of the curves above horizontal axis was different for each level
of humidity obtained during both the last cycle or the first cycle. This brought to the conclusion that final
humidity may be predicted/calculated upon obtaining of its level after the first cycles, i.e. after first 4 – 16
minutes plus the time required to fulfill intermediate weightings at the end of each cycle. Total time of
measurement so will vary between 4.5 and 18 min. So the algorithm idea was to dry the sample for short
time and to calculate the final humidity according to the mathematical model to be elaborated
experimentally. Besides this, there is another base to use this way. Researches carried out not once by
some scientists (1, 1), showed that fibrous part of seed cotton is accumulating about 43% of humidity of the
entire sample. It means that in case we know humidity of fibrous part, we may calculate the final humidity
of seed cotton sample. So, the combination of our own conclusions and the knowledge of the previous
researches prompted us to make a final decision to use the measurement of humidity of the fibrous part
for the further mathematical modeling of algorithm.

V. Main tests.
Series 1.
At the stage of statistics collection, all seed cotton samples were dried until almost dry, when the
difference between two consequent results was reasuring to the level of 0.01% or lower. At this stage
further drying is not changing result noticeably. Average duration of individual test was about 3 hours. The
reason for complete drying (while only first cycles results were used for further calculations), is that final
result was used for comparison with the standard method in order to make sure that both measurements
were carried out correctly. In case of any doubts, all results – of BRT, of standard method and of rapid
method, were being compared with each other, and decision was being made whether to accept obtained
result or repeat the measurement. All results were filled into Excel sheets (see the table Algorithm Series
1). They were used to create the graphs of the relationship between standard method readings and BRT
readings obtained at various stages of drying cycles.

Algorithms.
Several algorithms were offered and analyzed in this research.
The first one is based on assumption that final humidity is linked only with the humidity of the fibrous part
which is supposed to be completely determined after the first 4-minute cycle. So, columns No 1 and 5 were
used to create the graph, calculate correlation coefficient, standard deviation and create formula. Modeling
showed that this algorithm is not able to provide reliable results (for this reason accompanying graphs are
not shown herewith).
The second algorithm was based on the assumption that final humidity is linked with the humidity of
fibrous part and of upper layers of the seed peel (which, in turn, was supposed to be dried during the
second cycle). So, columns No 2 and 6 (humidity record after 8 minutes drying) were used for calculations.
Modeling was carried out for two different formulas created on the basis of linear and square relation between parameters of the equation. Modeling showed that both formulas provided better accuracy (standard deviation was 1.11% for the linear formula and 0.91% for the square formula (see last figure in the columns No 10 and 8). Nevertheless for the 95% confidence interval (which denotes double standard deviation and which is foreseen in the Uzbek standards), even the accuracy of 0.91% x 2 = 1.82% is not enough for the measurements.

The third used algorithm was based on the assumption that final humidity is linked with the accumulated humidity of fibrous part, entire seed peel and part of kernel humidity; this entire level of humidity was supposed to be evaluated during the first 3 cycles, i.e. 12 minutes of drying (plus 1.5 min of weighing time). So, individual result of 12 minutes (columns No 2 and 11) was used for calculation, and linear formula was obtained. This algorithm gave worse result compared to the 8-minutes algorithm - 1.19% of standard deviation. It means that the used assumption happened to be too simple and not taking into account the complexity of the subject. This was confirmed also by the additional modeling of the process, described here below.

The attempt was undertaken to create the theoretical curve fitting the real drying curve as close as possible. In case it is possible, there is no problem to calculate the final humidity having just one reading of the device. But modeling showed that it is unattainable. Nevertheless, if real curve is divided into 2, or better 3 segments, each of them can be modeled more or less closely. It indicates the complex character of drying process, which may consist of 3 individual processes. Supposedly we may assume that they are namely:

- fiber (lint) drying process. It is the most simple process of drying of porous medium.
- Seed peel drying process. It is more complex, but still more or less clear, as the drying of porous media is well investigated.
- Seed kernel drying process. This is the most complex process, especially as moisture movement should be considered in a colloid media of the kernel itself, then in the border between the kernel and thin layer of air, then at the border of air and seed peel, then in the peel itself. The general drying process is even more complex, as along with the peel drying process there is the opposite process taking place - humidification of seed peel by the moisture emanating from the seed kernel.

Taking into consideration all described above, the decision was made to involve all three mechanisms of drying into the formula. Besides this, the technical parameters of the regain tester itself should be taken into consideration. This is mechanical device which is subjected to possible random errors during physical execution of the measurement algorithm, for example during weighting of samples. Possible way of reducing them is to repeat weightings at least twice for each cycle. But this is impossible for timing reasons. Studying of the problem brought to the decision which enabled to merge both aspects: device's mechanical aspect and theoretical aspect of drying mechanism. Mechanical aspect: all three weighing readings (after 4, 8 and 12 minutes) were included into the formula in the form of their average reading. Thus possible mechanical random error was reduced, as these mistakes are multidirectional and they offset each other if added together. According to the statistical laws, the factor of reduction is $\sqrt{3} - 1.7$. Theoretical aspect: while taking only one cycle reading as an argument of the formula, we assume that there is only one drying mechanism and one simple correlation between this reading and final humidity. This was adopted for the previously developed algorithms, and they gave not precise results. As we saw from the drying curves, their shapes are not linear. For this reason, if we take the average of the first three readings, it will not coincide with the middle reading of 8 minutes, but it will better reflect the convex shape of the real curve, thus enabling more precise modeling of it. As a result, we may expect better precision of the formula which calculates the forecasted final humidity. So, the average of the first three readings of drying cycles was taken as an argument of elaboration of the formula. Data listed in the columns 2 and 18 of the table.

Before to start using this algorithm, some intermediate algorithms have been tested too. One of them (8+12 min) gave much better result of 0.55%, or 1.1% of accuracy for the 95% confidence interval. Nevertheless, the next algorithm involving of 3 readings (4+8+12 min) was elaborated in order to check if it can provide better accuracy. While testing different formulas, several types of them were looked through: linear, polynomial, logarithmic. Despite the expectation that logarithmic formula will be the best to be applied (as normally this kind of dependability is typical for natural processes, such as drying process
and others), the second degree polynomial formula appeared to be the most suitable. Indeed, relevant calculations showed that it is providing 0,43% of standard deviation, or 0.86% of accuracy (see column No.). Relevant graph is given at the picture No. along with the formula of the humidity calculation. This result may be considered as good for such type of indirect methods of measurements. Correlation between standard method results and BRT results was 0,9973.

Series 2.
In order to expand the investigated cotton range, it was decided to carry out the next series of tests using different varieties of cotton. So, one more set of samples was prepared and the tests were fulfilled similar to the previous series. Again, neither of cotton parameters were taken into consideration, meaning that samples had different botanical variety, trash content, micronaire, grade, lint outturn. Algorithm of calculations was chosen similar to the first series, i.e. the polynomial of the 2nd degree. Obtained results are shown in the attached table “Algorithm Series 2”. Formula is slightly differing from the 1st series, still keeping the similar type. Standard deviation is 0,83 (equivalent accuracy is 0,82x2=1.64%) which is sufficiently worse than in previous series. This may be caused by the possible random experimental errors, non-considering of samples’ parameters, and especially, non-uniform distribution of moisture in the samples during humidifying them. In order to receive more precise results, these parameters should be included into the algorithm.

Simultaneously with main tests, the statistical treatment of the results of the standard method was carried out. Standard deviation of individual results was varying from low 0,06% to high 0,64%. As mentioned earlier, only averaged results were used for calculations. As per statistical laws, the standard deviation of average values is \( \sqrt{\text{V of the number of repetitions less than of individual reading}} \). Its values are given in the column “STD of Average Reading” of the table. Statistical average of it is 0,19.

Unified results.
In order to obtain the common algorithm and evaluate the general accuracy of regain tester, results of both series were unified into one table, and general formula was elaborated (See attached “Unified Table”). Standard deviation of unified results was 0,80, meaning that accuracy is 1,6% of humidity. It is composed of the accuracy of regain tester and accuracy of the standard method. In order to obtain the general accuracy of the device itself, the squares of both values were deducted from each other and the square route was taken. Standard deviation of the device was calculated to be \( \sqrt{0,80^2 - 0,19^2} = 0,78 \). Accordingly, accuracy of the device is 0,78 x 2 = 1,56%.

Obtained result is not accurate enough for the industrial use. Nevertheless the first series demonstrated that acceptable accuracy is achievable. In order to obtain it, the wide-scale research needs to be carried out. It will develop the universal algorithm, involving all variables and influencing factors and enabling to reach acceptable level of accuracy not exceeding 1% of absolute humidity.