# DEVELOPMENT AND APPLICATION OF THE CURING INDEX FOR CUT-BACK ASPHALTS

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# PREFACE

This thesis, as submitted, consists of two parts: (1) an account of the development of the Curing Index, and (2) a mimeographed report which constitutes the laboratory data and theory on which the Curing Index is based. It also includes considerable data and facts on cut-backs in addition to the Curing Index. The mimeographed report was published in the Journal of Asphalt Technology, Volume 2, No. 6, 1943, and was the first announcement of a method for controlling the curing speed of cut-backs. The data presented represents possibly ten per cent of the data collected in attempting to solve our problem.

All of this work was done in the Texas Highway Department. Most of the work was done personally by the writer. Assistance rendered included laboratory tests by Mr. K. K. Moore, Mr. L. L. Wallace, and several others in the Asphalt Laboratory at Austin, Texas. Mr. A. C. Love rendered valuable assistance in writing the original published report.

The work began while Mr. E. B. Cape was materials engineer of the Texas Highway Department. At the time of the completion of the initial phase, Mr. R. J. Hank was materials engineer; and, in accordance with the common practice in many highway departments, the work was published under his name, the writer being given due credit in the first portion of the report.

Possibly the most valuable assistance given the writer came from the practicing engineers, refiners, and materials manufacturers. Without their help, the theory and data developed in the laboratory could never have been put into practical use, and it would have been buried in the files. Those of greatest assistance were Mr. E. V. Scott, General Manager, Southwest Stone Company, Dallas, Texas; Mr. H. S. Hudson, Technical Representative, Serv-tex Materials Company, New Braunfels, Texas; Mr. B. I. Scoggin, Manager, Research and Development, Anderson-Prichard Corporation, Oklahoma City, Oklahoma; and Mr. Guy Lott, District Manager, Texas Highway Department, Amarillo, Texas. Many others, too numerous to mention, contributed toward making practical use of the theory developed by the writer. Special acknowledgment is given to Mr. J. L. Worthington of the Creole Petroleum Company, Caracas, Venezuela, who informed me at our last meeting that it was his intention to introduce this method of control into South America, where cut-back asphalts are used almost exclusively.

Thus, the author must disclaim any credit except that which is due to the development of the ideas and theories themselves. The remainder of the credit must go to those enterprising gentlemen who were willing to try something new.

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# DEVELOPMENT AND APPLICATION OF THE CURING INDEX FOR CUT-BACK ASPHALTS

## DEVELOPMENT OF ASPHALT CUT-BACK PAVEMENTS

The first asphalt pavements built in the United States were composed of a mixture of asphalt and stone, which occurred as a natural deposit. Most of this material came from Europe.

As a natural outgrowth of the use of such material, engineers learned to make a paving mixture by coating hot aggregate with hot asphalt. The first asphalt used was taken from "asphalt lakes" where it occurred as a natural deposit.

About 1900, petroleum asphalts, obtained from crude oil began to replace natural asphalts. Petroleum asphalts have now replaced natural asphalts in the United States almost completely.

The first petroleum asphalts used were "asphalt cements." Asphalt cements are stiff, plastic materials at ordinary temperatures. However, they are thin enough to mix with stone at temperatures of about 250°F. or higher and it is therefore necessary to heat both the stone and asphalt in making a mix. Also, this mix must be kept hot until it is placed on the road and rolled to form the finished pavement. Upon cooling, the asphalt cement in the mix becomes hard, serving as a strong binder for the stone.

Engineers soon learned that the "thinning down" of the asphalt cement, which had always been accomplished by heat, could be accomplished in another way. Kerosene, gasoline, or naphtha added to the asphalt cement resulted in a thin solution of asphalt which could be mixed with stone at air temperature. Furthermore, by aeration, the liquid would lose its "thinner" by evaporation and revert back to a hard asphalt, similar to the asphalt cement from which it was made. Materials made by thinning down an asphalt cement are termed "cut-backs."

There were many advantages in the use of cut-backs and their use became wide spread. Up until 1932, there were about as many types of asphalts as there were engineers. In 1932, the U. S. Bureau of Public Roads (Now the Public Roads Administration) in cooperation with the Asphalt Institute set up specifications for four "Rapid Curing" and five "Medium Curing" cutbacks. These were later modified in 1939 to include six rapid curing and six medium curing cut-backs. These specifications are now in common use.

"Rapid" and "Medium" are supposed to refer to the curing rate of the material. The curing properties (or curing rate) of cut-backs has always been their most troublesome feature, particularly prior to 1940, before any means existed for measuring the curing rate.

## DIFFICULTIES ENCOUNTERED IN TEXAS

During the late thirties, the Texas Highway Department began using a certain cold-mix, termed Item 309-M[1], in large volume, and it is still being used in considerable quantity. Briefly, it is a mixture of crushed stone, ranging from a top size of 1/2" down to dust and RC-2 (Rapid Curing No. 2) Cut-back. The cut-back is of such viscosity that it may be mixed with the stone at about 125°F. If the cut-back used has the proper curing properties, the mix will stay workable for several days and hence it may be shipped by gondola car or truck to sites distantly located from the mixing plant. It is usually shipped by gondola car and is produced by three or four materials companies in Texas and Oklahoma.

When the mix arrives on the job, it is unloaded and placed on the road, where it is aerated, usually by means of a blade grader, until the asphalt has "stiffened" by curing, to a point that will furnish adequate binding power to produce a stable pavement. It is then rolled, and forms an excellent pavement, provided proper construction procedures have been followed.

All too frequently, this mix "backfired." Some of the mixes would "set up" in the car during transit to such an extent that it would be necessary to unload it with pitchforks. In one case, a plow was taken into the gondola car in order to loosen up the mix before unloading. The ideal mix could be easily unloaded with a clam-shell. In many cases the material would unload easily enough, but would require an excessive amount of blading in order to cure the mix sufficiently.

It was known that all these troubles came from the curing rate of the cut-back used. Those which set up in the car cured too rapidly while those which required excessive blading cured too slowly. The only means of judging the curing-speed was by the results of a distillation which was a part of the specifications. Unfortunately, visual inspection of the distillation results gave only the vaguest idea as to the curing speed. Their only value lay in the fact that the boiling range, or average boiling point of a cut-back, decreased as the curing speed of the cut-back increased. Many arbitrary methods for interpreting the distillation results were proposed, but all of them were disappointing when applied.

Due to the many advantages of this cold-mix, it was highly desirous to overcome the difficulties mentioned above. In 1940, the problem had reached such importance that it was decided to perform an investigation which would attempt to solve the curing problem for these mixes. This project was assigned to the writer.

## DEVELOPMENT OF METHOD

Evaporation Curves. A cut-back cures because the thinner (naphtha in the case of RC-2) evaporates, progressively thickening the asphalt which remains. Hence the problem consisted largely in a study of evaporation of liquids.

After an exhaustive survey of the literature, it was found that several investigators had proved the validity of an equation derived on a purely theoretical basis by Maxwell and Stefan in 1870,[2] which related evaporation rate to several physical constants of a liquid. The equation follows:

$$(1) \quad N_a = \frac{DP}{RTx} \frac{(P_{a_1} - P_{a_2})}{P_{BM}}$$

Where:
$N_a$ = Evaporation rate, mols per second per sq. cm.
$P_{a_1}$ = Partial pressure of vapor at liquid surface mm Hg.
$P_{a_2}$ = Partial pressure of vapor at distance X from liquid surface mm Hg.
$P_{BM}$ = The log mean of the vapor pressure of the air between the surface and point X above the surface.
$P$ = Total pressure, mm Hg.
$R$ = Gas constant
$T$ = Absolute temperature °K
$X$ = Effective stagnant film thickness of air above liquid surface

This equation contains so many variables that it is not practical for actual application. However, George S. Gardner[3] showed that it could be modified to the following form without appreciable error.

$$(2) \quad E = k(D_1 M_p)$$

Where:
$E$ = Evaporation rate grams/hr./sq. cm.
$k$ = $\alpha / RTP_x$
$\alpha$ = proportionality constant
$R$ = gas constant -- cc/atmospheres
$T$ = absolute temperature °K
$P$ = Total pressure atmospheres
$X$ = Effective thickness of film, cm.
$D_1$ = Diffusion coefficient at $P = 1$
$M$ = Molecular weight of evaporating liquid
$P$ = Vapor pressure of liquid, mm Hg.

Under constant conditions of air flow and temperature k will be constant in equation (2). Also for chemically similar liquids (light petroleum hydrocarbons), D may be expected to remain essentially constant. If the vapor pressure is expressed in #/in$^2$ instead of mm of Hg., another constant will be introduced. Also, if the surface area be kept constant, the evaporation rate may be expressed as %/hr., by multiplying E in equation (2) by a constant. If all these constants are combined into one constant k', we may now rewrite equation (2).

$$(3) \quad E = k'Mp$$

Where: $E$ = evaporation rate %/hr.
$M$ = molecular weight of liquid
$k'$ = constant
$p$ = vapor pressure #/in.$^2$

Equation (3) was assumed by the writer to apply to the evaporation rate of a pure liquid, coated on a definite weight of a definite stone at fixed conditions of temperature and air flow. In spite of the simplifications involved, theoretical considerations indicated that the error due to simplification would be negligible.

Following is an account of the manner in which equation (3) was utilized to provide a means of measuring the curing speed, or in actuality, the curing time of cut-backs under set conditions.

Briefly, the distillation on a cut-back is performed as follows: The cut-back is placed in a flask containing a thermometer, the flask is connected to a condenser and the thinner is distilled from the flask into a 100 ml graduate. As the distillation of the material in the flask increases, readings of the thinner in the graduate are made at the following temperatures, °F: 320, 347, 374, 437, 500, 600, and 680.

The results of an RC-2 distillation are shown in Table No. I.

Table No. 1

| Temp. °F. | % by Volume Distilled Over | ΔV | Fraction No. |
|---|---|---|---|
| Initial Boiling Point | 308 | | |
| 320°F. | .8 | .8 | 1 |
| 347 | 2.0 | 1.2 | 2 |
| 374 | 6.0 | 4.0 | 3 |
| 437 | 13.5 | 7.5 | 4 |
| 500 | 17.3 | 3.8 | 5 |
| 600 | 19.3 | 2.0 | 6 |
| 680 | 21.0 | 1.7 | 7 |

Equation (3) applies to a pure liquid with a given constant boiling point. It may be seen that the above distillation does not represent a pure liquid by any means, but instead has a boiling range of 372°F. Equation (3) would therefore represent an instantaneous evaporation rate at a point and would have to be expressed as a differential.

$$(4) \quad \frac{dv}{dt} = k'Mp$$

Where: $v$ = volume - %
$t$ = time in hours
$k'$ = constant
$M$ = molecular weight
$p$ = vapor pressure #/in.$^2$

From laboratory curves, approximate mathematical equations may be set up with M, p and v expressed in terms of the boiling point. The expression may then be integrated to give the total time required for the cut-back to evaporate to a given point.* However, such a procedure proved to be entirely unpractical, due to the necessity of obtaining equations from curves and also because the integrated expression was far too bulky to handle. Hence the following method of analysis was used.

The liquid coming over between any two given boiling points was considered as a pure liquid with average vapor pressure $p_x$ and average molecular weight $M_x$. The vapor pressure $p_x$ was obtained from the Cox Chart, which is a plot of temperature against vapor pressure for hydrocarbons of given boiling points. The vapor pressure at a temperature of 140°F. was chosen, because this is a maximum road temperature for asphalt pavements. The approximate molecular weight was determined on the individual fractions of naphtha from a number of cut-backs and an average obtained for each fraction.

Applied in this manner, equation (4) becomes

$$(5) \quad \frac{\Delta V}{\Delta T} = k'M_x p_x$$

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* See Appendix for integration procedure.

Expressing the reciprocal of k' as K, the time required for a given fraction to evaporate will be

$$(6) \quad \Delta T = \frac{K}{M_x P_x} \Delta V$$

The time T, required for the cut-back to evaporate to any given point will be

$$(7) \quad T = K \left( \frac{1}{M_1 P_1} (\Delta V_1) + \frac{1}{M_2 P_2} (\Delta V_2) \quad + \frac{1}{M_f P_f} (\Delta V)_f \right)$$

Where the subscripts refer to the successive fractions. The subscript $_f$ refers to the final fraction which may be, and usually is, only a portion of one of the fractions as shown in Table I.

## LABORATORY CONFIRMATION OF EQUATION (7)

Since all of the above is theory, it was necessary to make laboratory tests to see if equation (7) yielded results of sufficient accuracy for practical application. This was done by running evaporation tests on mixes with 19 different cut-backs, offering a wide range in type and curing properties.

The detailed procedure for making these tests is given in Curing of Cut-Back Asphalts, by R. J. Hank,[4] under "Appendix." Briefly, they were made as follows:

A mix was made with exactly 6.0% of cut-back, employing 200 grams of limestone aggregate in a 6 oz. ointment can. The grading of the aggregate is given below.

| Passing | Retained | Per Cent |
|---|---|---|
| 1/2" | 3/8" | 14.10 |
| 3/8" | 1/4" | 15.90 |
| 1/4" | 10 | 30.00 |
| 10 | 20 | 15.36 |
| 20 | 30 | 4.12 |
| 30 | 40 | 3.40 |
| 40 | 50 | 4.16 |
| 50 | 60 | 1.92 |
| 60 | 80 | 2.48 |
| 80 | 100 | 0.68 |
| 100 | 200 | 1.92 |
| 200 | | 5.96 |
| | Total - | 100.00 |

The mix was made at 140°F. and placed on a turntable in a 140°F. oven. At intervals, the mix was taken out and weighed to determine the loss in weight due to evaporation of the volatile thinner in the cut-back. This weight was determined quickly and the mix immediately placed back in the oven. The loss of volatiles in % by volume, based on the original cut-back, was calculated for each time interval. From the data a curve of time in hours plotted against % loss by volume was made for each cut-back. Typical curves are shown as dotted lines in Figure 1. of the attached article. The solid curves were those obtained by use of equation (7), with $K = 10$. K was obtained by comparing the actual evaporation curves with the theoretical ones obtained from equation (7). The theoretical curves were first plotted with $K = 1$. It was then a simple matter to obtain an average value of K by comparison of the actual and the theoretical curves. This value proved to be 10.

According to the assumptions employed in deriving equation (7), the product $Mp$ is a constant for any given distillation fraction. These were calculated for all the fractions that will be required in applying equation (7) and are shown in Table 3 of the attached article.

Actually, the curing of a cut-back may be defined as the increase in consistency of a cut-back due to the loss of its volatile thinner. Thus, any curve which purports to represent the curing characteristics of a cut-back should be a plot of time against consistency. Such curves were obtained as follows:

Consistency Curves. By consistency we mean the "thickness" or viscosity of a material. The fundamental unit of viscosity is the poise which is the ideal measure of viscosity. Another method commonly used for cut-backs is Furol-Saybolt Viscosimeter. It would have been desirable to employ the Furol viscosity in making our consistency curves, but it was impractical due to the wide range of viscosity represented by the cut-back from the initial to the final cured-out state. Another test was employed, known as the float test. The method obtaining the float test on cut-backs is given in ASTM method D-139. It is expressed in seconds, the viscosity increasing with an increase in time, expressed as seconds. Briefly, the test consists of pouring the material into a small cup about the size of a thimble, which is open at both ends, attaching this cup to a float, which holds the cup suspended in water, and observing the time required for the water to push the asphalt out of the cup.

Curves of float tests at 122°F. against per cent volatiles of by volume were obtained as follows:

The cut-back was subjected to the ASTM D-402 distillation but the distillation was stopped after a small amount had distilled over. The volume which had distilled over was recorded. A float test was made on the residue in the distillation which remained in the distillation flask. This procedure was repeated three more times, removing a little larger volume of the distillation each time. From this data, curves of float tests against distillate removed were plotted as shown in Figure 2 of the attached article.

Curing Curves. It will be observed that Figure 1 and Figure 2 are plotted using a common ordinate, namely the volatiles removed. By use of these curves, a new curve may be plotted in each case which will have float test as the ordinate and time as the abscissa. Such curves are shown in Figure 3. As an example, consider the curves for Sample No. 13 (RC-1). From Figure 1, the time at 10% volatiles off is 3-1/2 hours. From Figure 2, the float test at 10% volatiles off is 30. Three and one-half and 30 are the coordinates for a point on the curing curve shown in Figure 3. In this way, as many coordinates as desired are found and a smooth curve is constructed. This represents a true curing curve, because it shows the increase in consistency with time.

Curing Index. By use of considerable correlative data, it was established that the 309-M cold mix (mentioned previously as being widely used in Texas) was satisfactorily cured when the asphalt in the mix had reached a float test at

122°F. of about 120 seconds. Accordingly, it was decided to arbitrarily call this the cured-out point for all cut-backs. It should be stated here that there is no such thing as a definite cured-out point for cut-backs, as this will vary with the type of mix, grading, and other factors. However, this was of little moment to us, as our main objective was to set up a method for comparing the curing characteristics of cut-backs under set conditions. We therefore decided to call the number of hours required for the material to cure to 120 seconds float test at 122°F. as the Curing Index. This time was determined by application of equation (7). The justification for this was well established by a tabulation of the results of the Curing Index as obtained from actual evaporation curves and from the theoretical curves obtained from equation (7). This table is shown on Page 4 of the attached article. Observation of the curves in Figure 3 show that they approach a straight line and hence, the cured-out point, which might vary from 100 to 140 seconds float test under various conditions is not of great importance. This is because the ratios of the curing times will not vary greatly between a set of cut-backs, regardless of where the cured-out point is taken over the range mentioned.

So far as the writer was concerned, the Curing Index was only one feature of the curing curves and in order to predict the behavior of a cut-back under any condition, it would be necessary to have the curing curve and make observations over its entire range. The manner in which these observations are made and their significance is covered in the attached article under Flash-off During Mixing and Control of the Flash-off Point and the Curing Index. However, for some reason, those engaged in the manufacture of asphalts and asphalt mixes have never gone beyond the use of the Curing Index. It has been somewhat of a surprise to the writer that control of the Curing Index alone has resulted in considerable benefit to them in controlling their products. It is hoped that at some future date that the asphalt industry in general will made more complete use of such curves whether they be those developed by the writer or by some other method.

## APPLICATION OF THE CURING INDEX TO INDUSTRIAL CONTROL

Shortly after the paper on the curing of cut-back asphalts was published, one of the larger producers or cold-mix material in Texas and Oklahoma began specifying his cut-backs on the basis of the Curing Index. At the time he began doing this we had very little correlative information as to what ranges of Curing Indexes should be adopted in specifying cut-backs for a specific purpose. As a result of this producer's investigations, it was found that a cut-back with a Curing Index of around 35 was ideal for cold mix work. It was definitely established that curing indexes below 20 were almost sure to cause the mix to set up in the car; whereas, curing indexes above 60 always required excessive blading to remove enough of the volatiles to cure the mix out properly. The work of this producer was followed by others in Texas and it was found that little or no difficulty was experienced with the mixes as long as the Curing Index maintained between 25 and 45. These have now become fairly well accepted values for RC-2 cut-backs for general use. Jobs done in west Texas indicated that it was advantageous, for seal coat work, to employ cut-backs of a comparatively low curing index. No limits were ever established, but it appeared that the ideal range would be about 10 to 25. Unfortunately, no correlative work has ever been done with blade mixes, but it appears logical that the ideal range for a blade mix using RC-2 would be from about 45 to 60.

After the use of the Curing Index had become fairly common among the cold mix producers in Texas, some of the oil companies adopted the policy of adjusting the curing index on their cut-backs to about 35. According to verbal information from some of the refiners, this eliminated many of the complaints that they had with cut-backs. About one year after the article Curing of Cut-Back Asphalts appeared, two other methods were proposed for measuring the curing time of cut-backs. One was developed by Mr. F. N. Hveem of the California Department of Highways; the other by Mr. August Holmes of the Esso Corporation. In recent years, the asphalt industry has been increasingly conscious of the fact that they must have some numerical measure of the curing speed or the curing time of cut-backs. Hence, efforts have been made to standardize on some method. It appears at present that Mr. Hveem's method has been eliminated entirely due to the need of expensive equipment and also the time involved. The Asphalt Institute is now conducting a survey among a large number of laboratories in the United States which will yield comparative results on the Curing Index and the method proposed by Mr. Holmes. It is probable that one of these two methods will be adopted by the Asphalt Institute as a standard measure of designating curing time in numerical terms.

The writer realizes better than anyone that the Curing Index has shortcomings which should be overcome before it is adopted as an American Society of Testing Materials Standard and I am convinced that it will not be adopted by that body until those improvements are made. The main objection is the length of time required for obtaining the consistency curve for a cut-back. The larger state laboratories receive as many as 60 samples of asphalt in one day. Under present testing requirements, this represents about 80 man hours of work. For 60 cut-backs, the determination of the consistency curves would require about 60 man hours, so it may be seen that it will be difficult to ever introduce such a method into the routine testing of cut-back asphalts. Accordingly, the writer has been gathering information for the past few years in the hope that some method may be developed, which will enable us to determine the cured-out point of a cut-back with reasonable accuracy by means of theoretical considerations involving only the tests which are run in routine work.

Regardless of the method adopted, the writer feels that there is a crying need for some method which will definitely enable the engineer to predict the field behavior of a cut-back from simply obtained laboratory results. It is quite possible that the writer's method will not be the best approach. I have therefore maintained the position of promoting control of this feature by the method which appears to be best, rather than a promotion of my own method. It is my hope that this question will be settled within a few years. When it is, we will have made a great step forward in changing asphalt technology from an art to a science.

# DEVELOPMENT AND APPLICATION OF THE CURING INDEX FOR CUT-BACK ASPHALTS

## APPENDIX

### INTEGRATION OF EQUATION (4)

The following equation, (4) in the text, is the basic equation for obtaining the curing time of cut-backs.

$$(4)\quad \frac{dv}{dt} = k'Mp = \frac{Mp}{K}$$

Where: V = Volume evaporated, % by volume
t = Time in hours
K = Constant (established as 10.0 under actual test conditions)
M = Molecular weight of naphtha evaporating at given instant
p = Vapor pressure of residual cut-back at given instant

The quantity desired is the time, t, required for a given volume, V, to evaporate under the actual evaporation test conditions. See Page 1 of appendix in attached report for details of the evaporation test.

Briefly this is accomplished by expressing M, p, and dV in terms of X, the boiling point in the distillation test. In application the temperature $X_f$ corresponding to the desired volume $V_f$ is substituted in the integrated expression to obtain the time, t, required for evaporation of the given volume $V_f$.

Equation for p. By use of the Cox Chart, which is a plot of vapor pressure against temperature, a curve may be made with boiling point as the ordinate and vapor pressure as the abscissa, for a given temperature. This curve is essentially a straight line on a semi-log plot and a curve constructed for an evaporation temperature of 140°F. was found to have the following equation.

$$(a)\quad \frac{1}{p} = 10^{.01X - 2.8453}$$

Equation for M. A plot of the estimated molecular weight of the naphtha against the cut-back boiling point was found to have the following equation.

$$(b)\quad M = 10^{.000827X + 1.7585}$$

Development of Equation. If the distillation results for a rapid curing cut-back are plotted on semi-log paper with boiling point, X, on the log scale and volume distilled over V on the arithmetic scale, its approximate equation over a given limited portion of the curve will be as follows.

$$\text{(c)}\quad \log_{10}X = \frac{\log_{10}X_2 - \log_{10}X_1\ (V)}{V_2 - V_1} + \log_{10}t_i$$

Where: $X$ = boiling point, °F.
$V$ = volume distilled over cc
$X_1$, $V_1$, and $X_2$, $V_2$ are any points on a given straight line portion of the curve
$t_i$ = intercept of given straight line portion of curve at $V = 0$

For a given portion of the curve, the equation may be expressed as

$$\text{(d)}\quad \log_{10}X = mV + k \quad \text{or} \quad V = \frac{\log_{10}X - k}{m}$$

Where: $m = \dfrac{\log_{10}X_2 - \log_{10}X_1}{V_2 = V_1}$

$k = \log_{10}t_i$

Since V is expressed as a differential in equation (4), it is necessary to differentiate (d).

$$\text{(e)}\quad \frac{dv}{dx} = \frac{1}{MX} \cdot \log_{10}e \quad \text{or} \quad dv = \frac{1}{MX} \cdot \log_{10}e\,dx$$

Now, substituting equations (a), (b), and (e) in (4):

$$\begin{aligned}
dt &= (K)\left(\frac{10^{.01X - 2.8453}}{10^{.000827X + 1.7585}}\right) \cdot \left(\frac{\log_{10}e\,dx}{Mx}\right)\\
&= K\left(10^{0.009173X - 4.6038}\right)\frac{\log_{10}e\,dx}{MX}\\
&= K\left(\frac{e^{.02112X}}{10^{4.6038}}\right)\left(\frac{0.4343}{MX}\right)dx\\
&= \left[\frac{K(0.4343)}{M(10^{4.6038})}\ \frac{(e^{.02112X})\,dx}{X}\right]\\
&= \left[\frac{K(0.4343)}{M(4.016 \times 10^{4})}\right]\left[\frac{(e^{.02112X})\quad dx}{X}\right]\\
&= \left[\frac{K(0.108 \times 10^{-4})}{M}\right]\left[\frac{(e^{.02112X})\quad dx}{X}\right]
\end{aligned}$$

With:

$$K = 10$$

$$dt = \frac{1.08 \text{ X } 10^{-4}}{M} \quad \frac{(e^{.02112X}) \quad dx}{X}$$

$$\int_{t_1}^{t_2} dt = \frac{1.08 \text{ X } 10^{-4}}{M} \int_{X_1}^{X_2} \frac{(e^{.02112X}) \quad dx}{X}$$

The integration is performed by first expanding the numerator by use of McLaurin's series and then integrating each term.

The expansion is as follows:

$$e^{ax} = 1 + ax + \frac{a^2x^2}{2!} + \frac{a^3x^3}{3!} \cdot \cdot \cdot \cdot \cdot$$

Where:

$$a = .02112$$

$$\frac{1.08 \text{ X } 10^{-4}}{M} \int_{X_1}^{X_2} \frac{(e^{.02112X}) \quad dx}{X}$$

$$= \frac{1.08 \text{ X } 10^{-4}}{M} \left[ \int \frac{1}{X} + \int .02112 + \int \frac{.02112X}{2} + \int \frac{.02112X^2}{3} \cdot \cdot \cdot \cdot \cdot \right]$$

$$= \frac{1.08 \text{ X } 10^{-4}}{M} \left[ \log e \; X + .02112X + \frac{.02112X^2}{2! \cdot 2} + \frac{.02112X^3}{3! \cdot 3} + \frac{.02112X^4}{4! \cdot 4} \cdot \cdot \cdot \right]$$

From (d)

$$M = \frac{\log_{10} X_2 - \log_{10} X_1}{V_2 - V_1} = \frac{\log_{10} \frac{X_2}{X_1}}{V_2 - V_1}$$

Then

$$\text{(f)} \quad t = \frac{1.08 \text{ X } 10^{-4}(V_2 - V_1)}{\log_{10} \frac{X_2}{X_1}} \left[ \log_{10} X \; (2.303) + .02112X + \frac{(.02112X)^2}{2 \cdot 2!} + \frac{(.02112X)^3}{3 \cdot 3!} \cdot \cdot \cdot \right]$$

It is self-evident that this equation is not practical in application. Hence the use of the semi-empirical method described in the text was adopted.

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# CURING OF CUT-BACK ASPHALT

By

R. J. Hank[1]

## SYNOPSIS

This paper describes an investigation from which an attempt is made to develop a practical method by which the comparative curing speed of cut-back asphalts may be measured in numerical terms and thus provide a basis for their selection when used in the design of asphaltic concrete premixes.

In the use of the proposed method the curing of a cut-back asphalt is dependent on the increase in consistency (or viscosity) due to the progressive loss of volatile content, and a series of curves have been developed for application to RC and MC cut-backs in which one ordinate represents consistency and the other time.

## INTRODUCTION

The investigation described was brought about by the difficulty being experienced by producers in preparing plant mixes that could be shipped to a project and arrive in a condition where they could be unloaded without difficulty and which, with a minimum of curing time, could be rolled on the road and produce a satisfactory pavement. Some of the earlier mixes set up in the cars and extreme difficulty was experienced in unloading them. In an attempt to correct this, the producers reached the other extreme in which the mix cured too slowly.

In an attempt to solve the problem, Mr. J. R. Martin, a Chemical Engineer with the Materials and Tests Division of the Texas Highway Department, began an investigation. This resulted in the development of the method described. No claim is made that the method is the final answer to the problem because some of the assumptions may be questioned. It is offered as one method of approach that may be of use until a better method is found.

## MATERIALS

The first asphaltic materials used in the investigation were ten cut-backs from six different sources. Six of these reached the laboratory for routine testing to determine whether they met the specifications for various construction projects, and four were prepared in the laboratory. Later, one

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of the asphalt producers furnished three RC and four MC cut-backs especially prepared for the investigation in order to complete the series of cut-backs commonly used. Tests of these were used as a check on the materials previously investigated. Table 1 of the APPENDIX shows the results from the analyses of all of these materials. These materials met the specifications given in Table 2 of the Appendix.

Aggregate material for the investigation was secured from one of the producers who furnishes a large volume of premix to the Department. It was processed in the laboratory to meet the most frequently used grading requirements, this grading being given in the APPENDIX.

## CURVES

The use of curves in the solution of the problem is naturally the easiest method of application, and the explanation below shows how these were developed.

### Evaporation Curves:

The investigation was started with the thought that perhaps a simple evaporation test might be a method of control in the selection of materials for cut-back asphaltic concrete mixes. As the work progressed, it became evident that the simplest approach was by a test in which the cut-back asphaltic concrete mixes were placed in an oven of constant temperature and the loss of volatiles determined at intervals of time. The plotting of data obtained in this manner on various cut-backs resulted in the curves shown in Figures 1 and 4 by the dotted lines. The method of test is given in the APPENDIX.

The time required for the evaporation tests was objectionable, therefore, a formula was developed whereby the evaporation curves could be approximated with acceptable accuracy. The development of this formula is given in the APPENDIX and its results plotted as full lines in Figures 1 and 4.

### Consistency Curves:

Even before the completion of the evaporation tests, it was realized that the evaporation test alone would not give a complete indication of the curing characteristics of a cut-back, but that consistency must be considered.

In determining consistency Saybolt viscosity was not used because of the length of time required to make the tests nor could penetration be used because of the softness of the materials. The Float Test at 122°F. was therefore employed because it can be made quickly and is applicable over a wide range of consistencies. In order to use it in connection with the evaporation test, it was necessary to make a series of incomplete distillations on each of the materials, determine the distillation losses, and then subject the residues to the float test. From these data the curves shown in Figures 2 and 5 were plotted. The method of making incomplete distillation tests and the float test on the residues is given in the APPENDIX.

Curing Curves:

The evaporation and the consistency curves have a common ordinate consisting of percentages of volatiles lost. For any given percentage of volatile loss, the evaporation curve will give the time interval necessary in the oven at constant temperature to secure this loss. For the same percentage of loss and the same material, the consistency curve will give the corresponding consistency. These two values of time and consistency, when plotted against each other, result in the curing curves shown in Figures 3 and 6. In obtaining values from the evaporation curves the calculated or formula results were used.

For illustration in preparation of these curves, consider the calculated evaporation curves for sample No. 14, an RC cut-back. In Figure 1, for a 5% volatile loss, the time is two hours, and from Figure 2 the float test time for the same volatile loss is 27 seconds. From these values as ordinates a point on the curing curve was determined. In the same manner as many points as are necessary are determined for the construction of the complete curve. The construct'on of such curves for the RC and MC cut-backs then will provide a common basis for the comparison of their curing characteristics.

## CURING INDEX

It has been well established in the asphaltic concrete section of the Texas Highway Department Laboratory that this State's "cold mixes", using RC-2, are satisfactorily cured when not more than 0.4 per cent volatiles and/or water by weight remain in the mix. Such a percentage of volatiles corresponds to approximately 20 per cent of the total volatiles in the commonly used RC-2 cut-backs. Curves such as those shown in Figure 2 were obtained on a number of the RC-2's commonly used. From these it was found that the consistency of the RC-2 residues, at the point where they contained 20 per cent of their original volatiles, averaged around 120 seconds float test at 122° F. It was then assumed that a float test of 120 seconds at 122° F. could be designated as the "cured out" point for comparing the curing time of all RC and MC cut-backs. The time required to reach 120 seconds float test is designated as the "Curing Index".

As indicated, the "cured out" point has been investigated only for RC-2 cut-backs but it furnishes a value which, when applied to all cut-backs, provides a common basis for numerical comparison in curing time (Curing Index). When this has been correlated with field behavior, it will indicate the proper cut-back for use.

The Curing Index for all of the materials used in this investigation are given in the following tabulation. The calculated evaporation curves were employed in obtaining the Curing Indices and as a matter of comparison the curing time (to 120 seconds Float Test) employing the evaporation curves obtained by test are also included. From a comparison of these values, it appears that the use of the calculated evaporation curves is justifiable for practical purposes.

CURING TIME OF CUT-BACKS
(To 120 Seconds Float Test at 122°F.)

| Number | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 10 |
|---|---|---|---|---|---|---|---|---|
| Type | RC-2 | RC-2 | RC-2 | RC-2 | RC-2 | RC-2 | RC-2MA | RC-1M |
| Results by Test | 9 | 20 | 32 | 63 | 53 | 67 | 90 | 52 |
| Results by Calculation (Curing Index) | 10 | 15 | 30 | 60 | 51 | 73 | 116 | 46 |

| Number | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 |
|---|---|---|---|---|---|---|---|---|---|
| Type | RC-2 | RC-2 | RC-1M | RC-2 | RC-3 | MC-1 | MC-2 | MC-3 | MC-5 |
| Results by Test | 41 | 58 | 21 | 26 | 17 | 650 | 400 | 270 | 55 |
| Results by Calculation (Curing Index) | 37 | 52 | 19 | 25 | 14 | 602 | 390 | 327 | 58 |

This tabulation is interesting because it brings out some of the reasons for this investigation. Asphalt No. 1 (RC-2) was actually used on a construction project; the mix set up in the car and was very difficult to unload. The material approximating No. 3 (RC-2) gave acceptable results, while one of the field engineers complained that he had great difficulty in curing out the No. 4 (RC-2).

The tabulation shows very definitely that if a reasonable curing time is desired, none of the MC cut-backs investigated are satisfactory, except possibly the MC-5.

It also is interesting to compare the extremely wide range of the Curing Indices shown for the two types of cut-backs which vary from 10 for the fastest curing RC to 602 for the slowest MC. The range of 10 to 73 for the RC-2's is surprising when it is considered that all of them meet the same specifications.

Effect of Distillate Content:

The MC-1, MC-2, MC-3, and MC-5 were all made with essentially the same grade of asphalt and the same kerosene as the distillate. The only variation in them that might affect their curing time is the amount of kerosene contained. Figure 7 shows the curve obtained when plotting the Curing Indices against the total distillate removed at 680° F. This figure shows the Curing Index decreases rapidly with decreasing distillate content and that the MC-5 has a Curing Index of only 55, or within the range for RC materials.

Effect of Penetration of Residue:

The effect of penetration of residue on curing time is well illustrated in the three samples of RC cut-back in Figure 3. These samples were all made using the same cutter-stock, and if the same asphalt had been used for all of them, their curing curves would have "nested" as did those for the MC's in Figure 6, and the curing curve for sample No. 14 would have fallen between the other two. No. 14 was made with a softer asphalt which caused its Curing Index to be greater than either of the others.

## FLASH-OFF DURING MIXING

The amount of volatiles in a cut-back asphalt is a measure of its consistency and the consistency at the completion of mixing is an indication of what may be expected of the "unloadability" when the mix reaches its destination. Some of the volatiles are always lost during mixing and this increases the consistency which, if increased to too high a point, will cause the mix to "set up" in the car and be difficult to unload. On the other hand if the consistency is too low upon completion of the mixing, the asphaltic material will drain from the stone. Both of these conditions should be avoided; therefore, proper consistency is a compromise between the two. The loss of volatiles upon the completion of mixing then has a definite bearing in the design of cut-back asphaltic concrete.

During the operation of mixing a cut-back with aggregates, the rate of evaporation of the volatiles is greatly accelerated and a portion of the volatiles will be lost or "flashed off" during the mixing period. For this reason the curing of a mix in an oven in the evaporation test always begins with a part of the volatiles already lost during mixing, and when the evaporation curve is constructed from the test data, it never begins at 0 per cent volatiles evaporated but at some higher point on the ordinate, its position being dependent upon the volatility of the cut-back.

The mixing conditions in the evaporation test were the same for all of the cut-backs tested and it is logical to expect their evaporation curves to extrapolate back to a common point. This was found to be true - all of them extrapolating back to about minus 1-1/2 hours. Points on the dotted curve in Figures 1 and 4 were all moved to the right 1-1/2 hours to give a proper comparison with the solid curves, points for which were determined by calculation.

With the shifting of the evaporation curve in order that zero volatile loss corresponds with zero time, the curves may be used to determine volatile losses during mixing. A vertical line drawn up from a time of 1-1/2 hours (which line may be called the "flash off ordinate") will intersect the evaporation curve opposite the volatile loss, or "flash off" during the mixing operation. In Figure 1 for instance, the ordinate through 1-1/2 hours will intersect the evaporation curve for sample No. 13 at 5.5 per cent volatiles evaporated during mixing. This corresponds with the actual loss determined from test. This relation will hold true if the mixing conditions are the same as in the original test. If the mixing conditions are more severe due to higher mixing temperature and/or increasing the mixing time the "flash off ordinate" will be greater than 1-1/2 hours, its value depending on the severity of the mixing conditions. For constant mixing conditions and the same mix design it should be expected that this relation would hold for materials mixed at commercial premix plants and this was found to be true. Data from routine inspection reports from premix plants where mixing conditions were constant showed a satisfactory approximation to the results from curves. In data obtained from one plant, which included 30 tests and represented one month's operation, the "flash off ordinate" averaged 3 hours, never falling below 2 hours, and exceeded 4 hours in only one test. These data involved mixes all using the same design except for slight variations in asphalt content. The calculated curve was used in all cases in determining the "flash off ordinate".

The significance of the "flash off ordinate" may be illustrated using the average of 3 hours. Reference to Figure 3 shows the 3-hour ordinate to intersect the curing curve for sample No. 14 at a float test value of 30 seconds; or, in other words, the "flash off point" for mixing is 30 seconds float test. If a railroad car of premix made at this plant is found to be difficult to unload when it reaches its destination, due to the mix "setting up" in the car, then with the same mix design even more difficulty could be expected with any cut-back, the curing curve for which intersects the 3-hour ordinate at a float test value exceeding 30 seconds, as long as the unloading temperature is about the same. Thus, the idea presents itself that with sufficient field data and correlation, involving several different unloading temperature ranges, limits for the consistency of the cut-back at its "flash off point" might be set up and those cut-backs causing trouble through setting up in the car eliminated by laboratory tests.

## CONTROL OF THE FLASH OFF POINT AND THE CURING INDEX

Regardless of where the "flash off ordinate" exists at a certain plant under given mixing conditions, it is certain that the "flash off point" may be reduced by lowering the initial viscosity with the addition of naphtha so long as the Curing Index is not appreciably decreased. By adding a naphtha which is slightly more volatile than that already existing in the cut-back, the "flash off point" may be lowered without appreciably changing the Curing Index in either direction. The result is that the "unloadability" is improved without appreciable effect upon the curing time.

This investigation was completed before the present Federal specifications went into effect. Under the new specifications, it was found that mixes from a certain plant made with the new RC-2 would set up in the car to a much greater extent than those made with the old RC-2. The addition of the cheapest grade of gasoline to the new RC-2 resulted in mixes that were easily unloaded.

It is obvious that the addition of heavier cutter-stock will increase the Curing Index and at the same time lower the "flash off point". Additions of heavier oils such as lubricating oils or heavier crudes will increase the Curing Index, but their effect on the initial viscosity and, consequently, the "flash off point" is small compared with that obtained with the same amount of naphtha.

It is not practical to attempt to reduce the Curing Index by an additive, however, it may be controlled at will in manufacture by the selection of the proper naphtha or by blending of stock naphthas of respectively low and high volatility. For a given Curing Index, the "flash off point" is largely a function of the initial viscosity of the cut-back, and therefore may be controlled by the amount and kind of naphtha used in its manufacture.

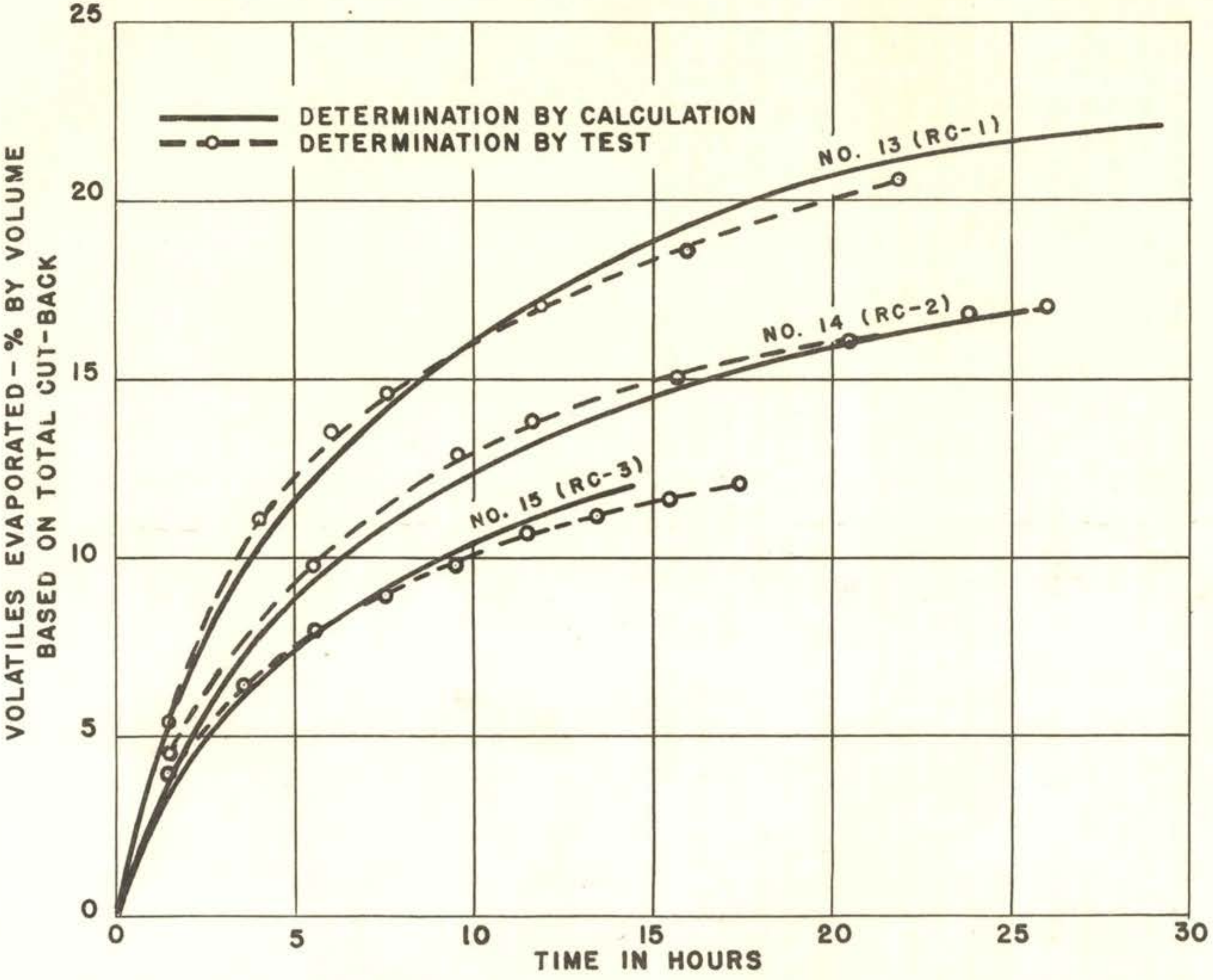

FIGURE I. EVAPORATION CURVES – RC CUT-BACKS

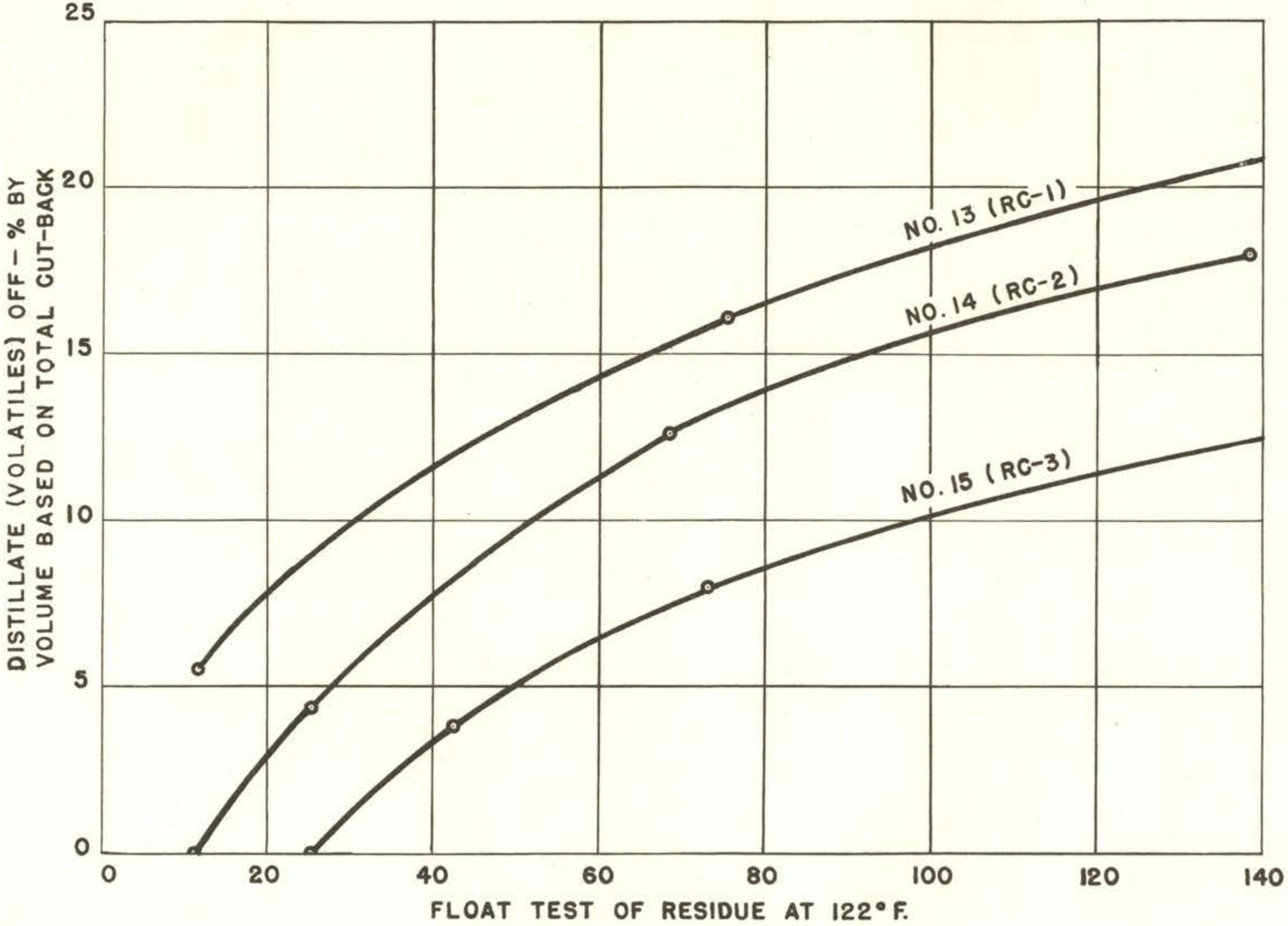

FIGURE 2. CONSISTENCY CURVES — RC CUT-BACKS

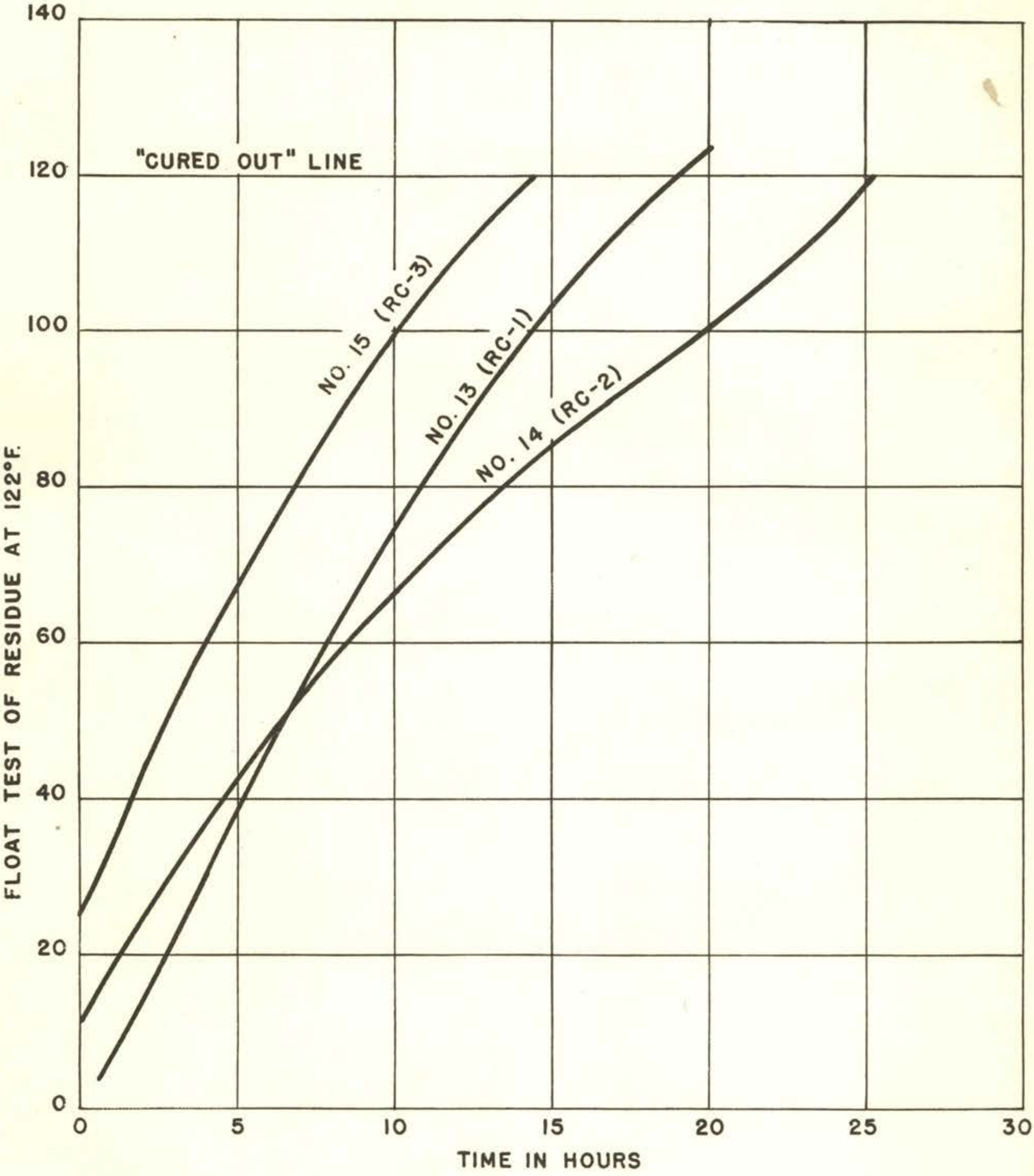

FIGURE 3. CURING CURVES– RC CUT-BACKS

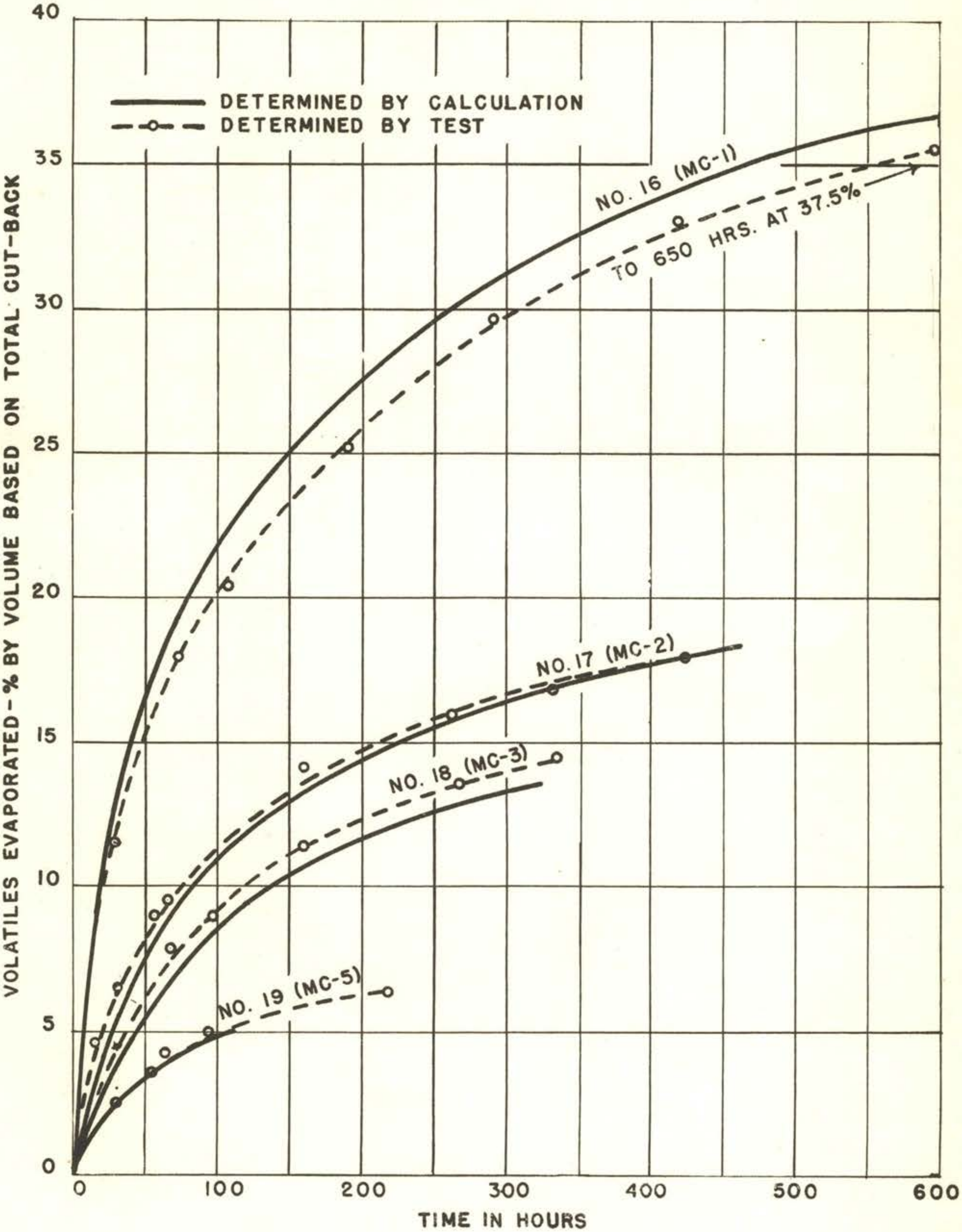

FIGURE 4. EVAPORATION CURVES—MC CUT-BACKS

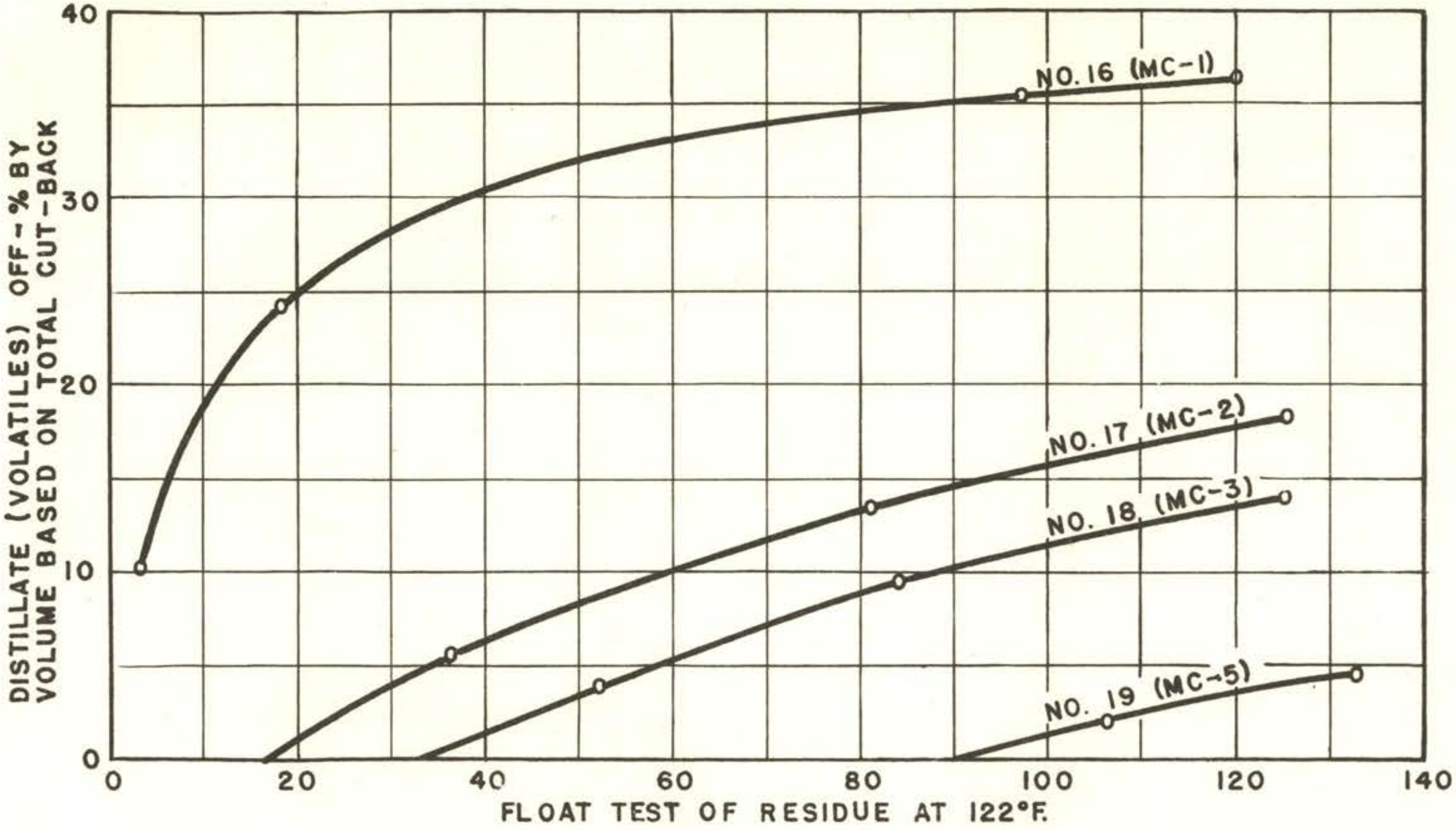

FIGURE 5. CONSISTENCY CURVES— MC CUT-BACKS

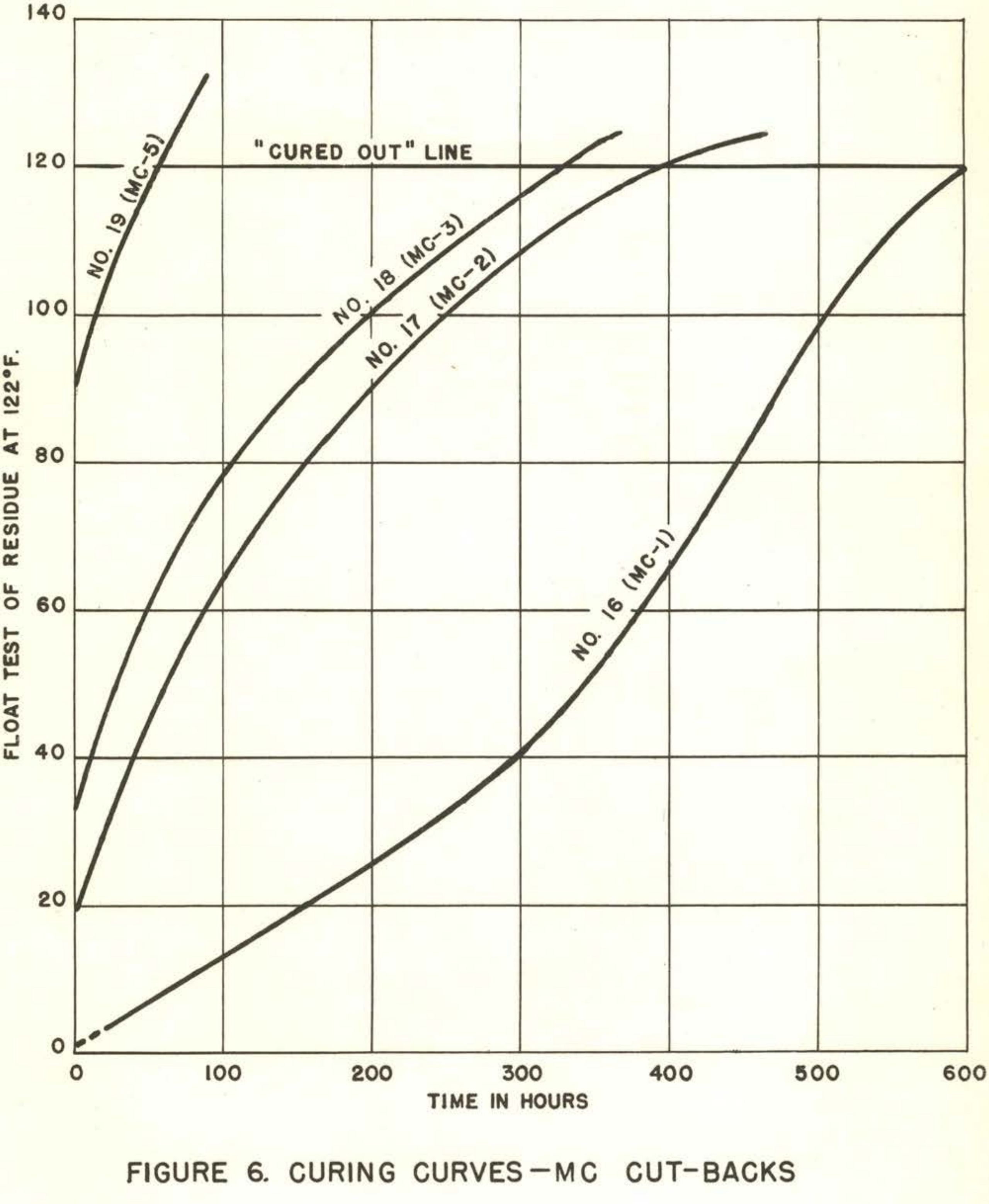

FIGURE 6. CURING CURVES—MC CUT-BACKS

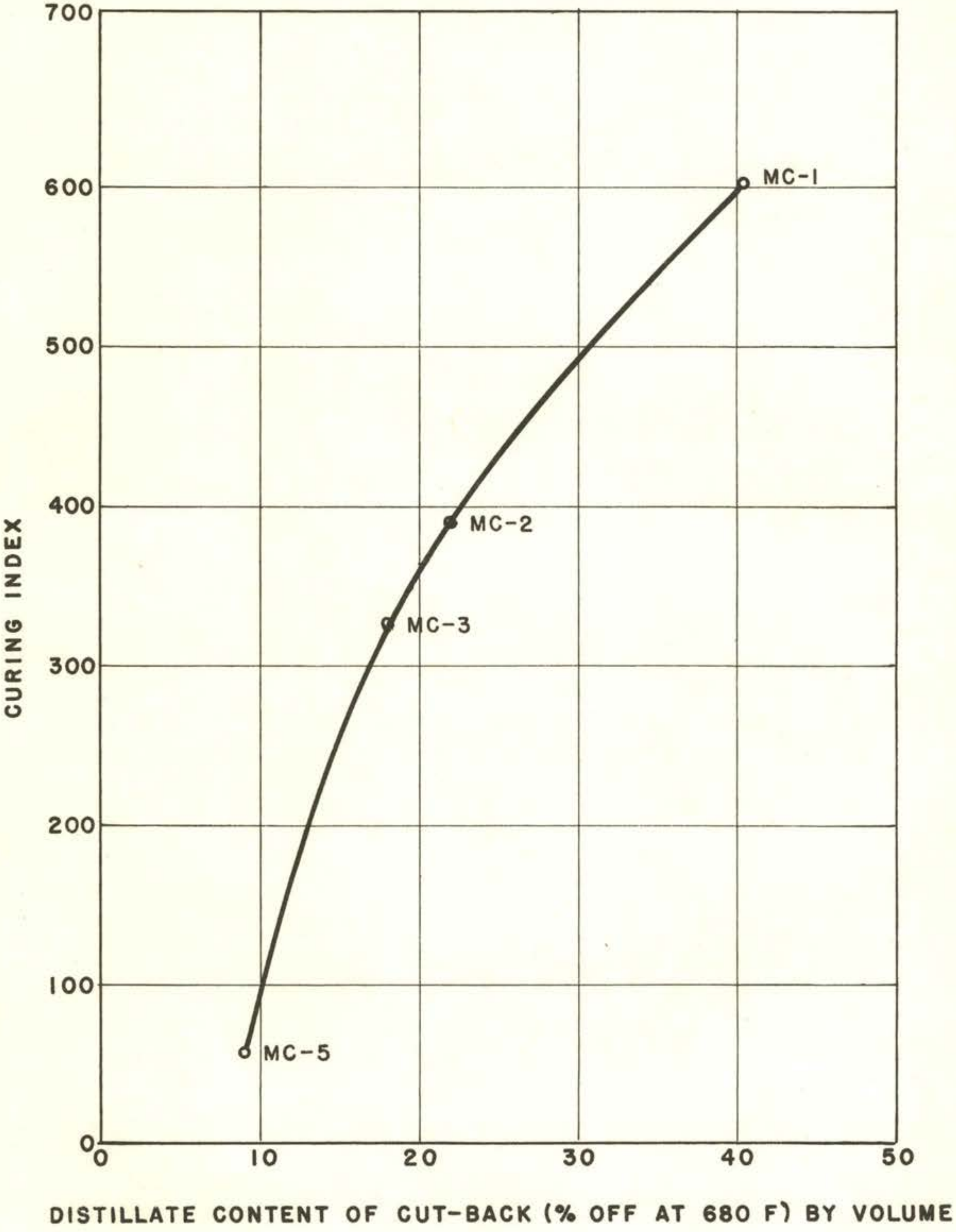

FIGURE 7. RELATION OF CURING TIME
TO TOTAL DISTILLATE CONTENT
MC CUT-BACK

## APPENDIX

### EVAPORATION TEST

Two hundred grams of an aggregate meeting the following grading requirements were placed in an 8-oz. tin ointment can:

| Passing | Retained | Per Cent |
|---|---|---|
| 1/2" | 3/8" | 14.10 |
| 3/8" | 1/4" | 15.90 |
| 1/4" | 10 | 30.00 |
| 10 | 20 | 15.36 |
| 20 | 30 | 4.12 |
| 30 | 40 | 3.40 |
| 40 | 50 | 4.16 |
| 50 | 60 | 1.92 |
| 60 | 80 | 2.48 |
| 80 | 100 | 0.68 |
| 100 | 200 | 1.92 |
| 200 | | 5.96 |
| | Total | - 100.00 |

A mixing spatula was laid across the can and the whole assembly weighed on a balance with an accuracy of 0.01 gram. The assembly then was placed in an oven and heated to a mixing temperature of 140° F. Twelve and eight-tenths (12.8) grams (or as near to as possible) of cut-back asphalt were added from a glass stoppered weighing bottle, the weight of the bottle and contained cut-back asphalt having been previously obtained. The mix was stirred for 5 minutes, compressed with the spatula, weighed quickly and the assembly placed in the oven immediately. The glass stoppered bottle from which the cut-back was taken was then weighed on the balance. The difference between this weight and the original weight gave the weight of the cut-back actually used in the mix. This weight added to the assembly weight of can, aggregate and spatula gave the weight without any volatile loss. The difference between this weight and the weight after mixing gave the weight of the volatiles lost during mixing which has been designated as the "flash off".

The assembly was removed from the oven at definite time intervals, weighed as quickly as possible and returned to the oven. The volatile loss by weight was determined and recorded for the corresponding time. With these data and that shown in Table 1, points for the evaporation curve were determined from the following formula:

$$\frac{100(L_t)V_c}{W(100-A)} = L_{vt}$$

in which

$L_t$ = weight loss in volatiles for time t (test)
$W$ = weight of cut-back asphalt (actual)
$A$ = % asphalt by weight in cut-back (Table 1)
$V_c$ = % volatiles by volume in cut-back at 680° F. (Table 1)
$L_{vt}$ = % loss by volume in cut-back (point on curve)

The Standard A.S.T.M. D-6 asphalt heat loss oven was employed in making the tests, the samples being allowed to rotate on the turn-table in the usual manner.

Test for Cut-Back Consistency at Various Volatile Contents

The data represented by the curves shown in Figures 2 and 5 were obtained as follows:

Each cut-back was put on to distill in the usual routine manner for the A.S.T.M. D 402 test. Instead of distilling it completely, however, the fire was cut off when only part of the distillate was over, the flask was allowed to cool, the exact per cent by volume which had distilled over was recorded and the float test at 122° F. was determined on the residue. This procedure was repeated several times, each time allowing a little more of the distillate to come over before the fire was cut off. Thus, a set of values was obtained for each cut-back from which the consistency curves were made.

## DERIVATION OF THE CUT-BACK EVAPORATION FORMULA

By use of the original Maxwell Stefan equation[1] for evaporation George S. Gardner[2] developed the following equation for the "rate of evaporation at a definite point on a liquid surface."

$$E = k(D_1 M p_{A1}) \text{ - - - - - - - - - - - - - - - - } (1)$$

in which

$E$ = evaporation rate, grams/hr./sq. cm.
$k$ = the group $\propto/RTPX$.
$\propto$ = proportionality constant
$R$ = gas constant, 82.07 cc/atm
$T$ = absolute temperature, degrees Kelvin
$P$ = total pressure, atmospheres
$X$ = distance in direction of diffusion through stagnant film, cm.
$D_1$ = diffusion coefficient under one atmosphere pressure
$M$ = molecular weight of evaporating liquid
$p_{A1}$ = vapor pressure of evaporating liquid, mm./mercury

Gardner derived this equation with the object of developing a constant which would "serve as a reliable expression of the relative evaporation rates of liquids under identical conditions, and which would be simple enough to be of practical value in industry." He proposed the term $D_1 M p_{A1}$ as the "Evaporative Index" to be applied to pure liquids.

In the application of the equation for this investigation it was assumed that if mathematical precision be neglected to the extent that variations within a narrow range could be treated as constant quantities, a method might be evolved, based on Gardner's equation by which the evaporation curve for asphaltic cut-back obtained by the evaporation test could be approximated with acceptable accuracy. The derivation of this equation is as follows:

The evaporation rate in Gardner's equation is expressed in grams per hour per square cm. For use in this investigation, it is desirable to express the rate as percentage by volume of total sample per hour. For convenience, vapor pressure has been taken from Cox's chart in pounds per square inch while Gardner's equation expresses it as mm. of mercury. In order to convert the equation to get the evaporation rate in per cent by volume of total sample per hour, with vapor pressure in pounds per square inch so that Cox's chart may be used, it is necessary to introduce the following factors: specific gravity of the sample; specific gravity of the evaporating liquid; a factor converting mm. of mercury to pounds per square inch; the surface area of the area exposed to evaporation; and the weight of the sample. With these factors introduced the equation becomes:

$$E_{\%} = \frac{100\ G_o\ kAD_1\ (Mp)}{G_1\ f\ W} \tag{2}$$

in which

$E_{\%}$ = evaporation rate, per cent by volume of total sample per hour
$G_o$ = specific gravity of sample
$G_1$ = specific gravity of the evaporating liquid (specific gravity of the distillate portion of a cut-back)
$A$ = surface area exposed to evaporation, sq. in.
$k$, $D_1$ and $M$ = same as in equation (1)
$P$ = vapor pressure in lbs. sq. in.
$f$ = factor converting mm. of mercury to lbs./sq. in.
$W$ = initial weight of sample

Under identical experimental conditions involving the evaporation of light hydrocarbons, the group $100\ G_o\ kAD_1/G_1\ f\ W$ will retain constant except for $G_o/G_1$ and $D_1$ whose variations are extremely small in comparison to Mp. this group has therefore been designated as k' and the equation then becomes:

$$E_{\%} = k'Mp. \tag{3}$$

$E_{\%}$ is equal to the evaporation loss at stated intervals of time and therefore may be written as $\triangle\%/\triangle t$. The equation then will read

$$\frac{\triangle\%}{\triangle t} = k'Mp \tag{4}$$

The results of the routine cut-back distillation test (A.S.T.M. D-402) may be reported in percentages by volume at the following temperatures Fahrenheit, 320°, 347°, 374°, 437°, 500° and 680°. If each fraction (% by volume distilling off between any two successive temperatures) is considered as a separate liquid with average vapor pressure $p_x$ and average molecular weight $M_x$, then equation (4) may be applied to any fraction, and $(\Delta t)_x$ will be the time required for the fraction $(\Delta\%)_x$ to evaporate, or

$$(\Delta t)_x = \frac{1}{k'M_xp_x} (\Delta\%)_x \text{ - - - - - - - - - - - - - - - } (5)$$

The time required for any designated per cent of the volatiles to be lost will therefore be equal to the sum of the time required for each successive fraction. Designating the total time as T and denoting the reciprocal of k' as K, the equation may be written:

$$T = \frac{K(\Delta\%)_1}{M_1p_1} + \frac{K(\Delta\%)_2}{M_2p_2} + \frac{K(\Delta\%)_3}{M_3p_3} + \text{ - - - } \frac{K(\Delta\%)_y}{M_yp_y} \text{ - - } (6)$$

In which the subscripts 1, 2, 3, refer to distillation fractions and subscript y refers to the last distillation fraction considered in the calculation.

Application of the Cut-Back Evaporation Formula:

The average molecular weight of the distillate coming over between each specified temperature in the routine cut-back distillation was determined as follows: The A.S.T.M. D-402 distillation was made on a number of cut-backs, after which the Engler distillation was made on the distillate from each. By plotting the results of the two distillations for each cut-back on one sheet, the Engler boiling points corresponding to the A.S.T.M. D-402 boiling points (320° F., 347° F., etc.) were determined in each case and the average found for all cut-backs. From a curve of molecular weight vs. Engler Boiling Points[3] it was possible to assign molecular weights to the A.S.T.M. D-402 boiling points and from those data to calculate the average molecular weights for each fraction. Molecular weights obtained in this manner are not absolutely accurate when applied generally, but have proven to be sufficiently accurate to be applied practically in equation (6).

By a cross plotting of the Cox's chart[4], a curve for any given temperature may be constructed with Boiling Point in degrees F. as the abscissa and vapor pressure in pounds per square inch as the ordinate. From such a curve, with 140° F. as the temperature the average vapor pressure for each fraction was determined.

Correlative calculations between the evaporation curves from tests and calculated curves gave $K = 10$.

Values of 10/Mp for each boiling point fraction were calculated and are tabulated in Table 3.

Sample Calculations for Curing Index and Evaporation Curve

Sample No. 14

| (1) Distillation (ASTM D 402) | | (2) | (3) | (4) | (5) |
|---|---|---|---|---|---|
| | | $\Delta\%$ | $10/M_p$ | $\Delta T$ | T |
| Boiling Point °F. | % Off by Vol. | | | | |
| 308 | IBP | | | | |
| 320 | .75 | .75 | .25 | .19 | .19 |
| 347 | 2.0 | 1.25 | .30 | .38 | .57 |
| 374 | 6.0 | 4.00 | .51 | 2.04 | 2.61 |
| 437 | 13.5 | 7.50 | 1.30 | 9.75 | 12.36 |
| 500 | 17.3 | | | | |
| 600 | 19.3 | | | | |
| 680 | 21.0 | | | | |
| "Cured-out" Point | 16.8 | | | | |
| "Cured-out" Temp. | 490°F. | 3.3 | 3.97 | 13.10<br>*25.46 | 25.46 |

*Curing Index = 25 to nearest whole number.

Steps in Calculation:

(1) Record the complete distillation for the cut-back as shown in Column (1).

(2) Determine the cured-out point from the consistency curve, Figure 2, (in this case, 16.8%) and record in Column (1).

(3) Calculate, by extrapolation, the "cured-out" temperature or the temperature at which 16.8% has distilled over. Inspection of the distillation shows that 16.8% is over somewhere between 437 and 500 degrees.

% at x° = 16.8
% " 437° = 13.5
Difference 3.3%

% at 500 = 17.3
% " 437 = 13.5
Diff. 63° 3.8%

(Cont'd. on Sheet #6)

$x^{\circ} = \frac{3.3}{3.8}(63) + 437 = 491.7$ or 490 to the nearest 10° F.

Record this value as the cured-out temperature.

(4) Record the difference between sucessive cuts of the distillation in Column (2). Record each one up to and including the one from 437 to 490° F.

(5) From Table 3 obtain the value of 10/Mp for the boiling point interval or cut represented by each △%.

Initial Boiling Point - 308° F. or 310° F. to the nearest 10°.

From Table 3, 10/Mp for the initial cut is .25 (boiling point interval from 310 to 320° F.)

10/Mp for intermediate cuts are .30, .51 and 1.30 for boiling point intervals 320° - 347°, 347° - 374° and 374° - 437°, respectively.

10/Mp for the final cut is 3.97 (boiling point interval 437° - 490°F.)

(6) Obtain the products of the values in Columns (2) and (3) and record in Column (4). The sum of these values is the "Curing Index."

If the complete evaporation curve is to be plotted, the progressive sums of the values in Column (4) are recorded in Column (5). The values in Column (1) are then plotted against the values in Column (5).

## TABLE 1

### ANALYSES OF CUT-BACKS

| NUMBER<br>TYPE | 1<br>RC-2 | 2<br>RC-2 | 3<br>RC-2 | 4<br>RC-2 | 5<br>RC-2 | 6<br>RC-2 | 7<br>RC-2MA | 10<br>RC-1M | 11<br>RC-2 | 12<br>RC-2 | 13<br>•RC-1 | | 14<br>RC-2 | 15<br>•RC-3 | | 16<br>MC-1 | 17<br>MC-2 | 18<br>MC-3 | 19<br>•MC-5 | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Flash °F. | 85 | 95 | 95 | 105 | 95 | 130 | 135 | 80 | 95 | 120 | 100 | | 110 | 115 | | 160 | 185 | 185 | 190 | |
| Fur. Visc. at 77°F. | | | | | | | | | | | | | | | | 132 | | | | |
| " 122°F. | 265 | 267 | 251 | 248 | 233 | 225 | 292 | 129 | 261 | 225 | 125 | | 246 | | | | | | | |
| " 140°F. | | | | | | | | | | | | | | 302 | | | 218 | 438 | | |
| " 180°F. | | | | | | | | | | | | | | | | | | | 355 | |
| Pen. of Res., 77°F. | 147 | 145 | 145 | 150 | 144 | 140 | 150 | 83 | 135 | 139 | 80 | | 124 | 92 | | 142 | 118 | 118 | 139 | |
| Duct. of Res., 77°F. | 110+ | 110+ | 110+ | 110+ | 110+ | 104 | 110+ | 115+ | 115+ | 110+ | 110+ | | 110+ | 110+ | | 110+ | 110+ | 110+ | 110+ | |
| Sol. of Res. (%) | 100.0 | 100.0 | 100.0 | 100.0 | 99.99 | 99.73 | 99.95 | 99.90 | 99.92 | 99.69 | 99.89 | | 99.92 | 99.93 | | 99.96 | 99.95 | 99.92 | 99.97 | |
| Asph. Res. by Wt. (%) | 82.6 | 81.7 | 81.0 | 79.8 | 79.0 | 81.8 | 81.8 | 73.0 | 76.3 | 78.3 | 78.4 | | 83.2 | 86.0 | | 65.3 | 82.2 | 85.4 | 93.0 | |
| Sp. Gr., 77°F. | .940 | .945 | .943 | .944 | .951 | .969 | .945 | .937 | .940 | .935 | .960 | | .964 | .979 | | .939 | .974 | .981 | 1.00 | |
| Dist. by Vol. (% of Cut-back) | | | | | | | | | | | | (% of Dist.) | | | (% of Dist.) | | | | | (% of Dist.) |
| I.B.P. | 230 | 236 | 300 | 376 | 300 | 320 | 350 | 280 | 330 | 374 | 300 | | 308 | 320 | | 422 | 456 | 468 | 476 | |
| Off at 320°F. | 8.5 | 5.0 | 1.5 | 0 | 0.5 | 0 | 0 | 2.0 | 0 | 0 | 1.0 | 4 | 0.75 | 0.0 | | | | | | |
| " " 347°F. | 11.0 | 9.0 | 4.0 | 0 | 1.5 | 0.5 | 0 | 5.0 | 1.0 | 0 | 5.0 | 19 | 2.0 | 1.4 | 8 | | | | | |
| " " 374°F. | 13.0 | 11.5 | 8.0 | 0 | 6.5 | 2.5 | 1.5 | 12.0 | 5.0 | 0 | 10.5 | 40 | 6.0 | 4.0 | 22 | 0.0 | | | | |
| " " 437°F. | 17.5 | 17.0 | 15.0 | 13.0 | 14.5 | 11.0 | 11.5 | 21.5 | 15.5 | 14.5 | 18.5 | 70 | 13.5 | 10.5 | 58 | 1.5 | 0.0 | 0.0 | 0.0 | |
| " " 500°F. | 20.0 | 20.0 | 19.0 | 19.0 | 20.0 | 16.5 | 16.0 | 25.5 | 21.5 | 22.0 | 22.0 | 83 | 17.3 | 14.2 | 78 | 20.5 | 5.5 | 3.0 | 1.0 | 11 |
| " " 600°F. | 22.0 | 22.0 | 22.0 | 23.5 | 23.5 | 20.0 | 21.0 | 30.0 | 26.5 | 25.5 | 25.0 | 94 | 19.3 | 17.0 | 93 | 35.0 | 17.0 | 13.0 | 5.0 | 55 |
| " " 680°F. | 23.0 | 23.0 | 23.5 | 25.0 | 26.0 | 22.5 | 23.0 | 33.0 | 29.0 | 27.0 | 26.5 | 100 | 21.0 | 18.2 | 100 | 40.5 | 22.0 | 18.0 | 9.0 | 100 |

*Made under Asphalt Institute Specifications. All others made under Standard Texas State Highway Department Specifications. See Table 2.

## TABLE 2

### CUT-BACK SPECIFICATIONS

** Texas Highway Department Standard Specifications

| Grade | RC-1M | RC-2 | RC-2MA | MC-1 | MC-2 | MC-3 |
|---|---|---|---|---|---|---|
| Limits | Min-Max | Min-Max | Min-Max | Min-Max | Min-Max | Min-Max |
| Flash °F. | 80 | 80 | 80 | 80 | 150 | 150 |
| Visc. (Furol) 60 cc | 100-160 (122°F) | 200-275 (122°F) | 200-275 (122°F) | 110-150 (77°F) | 150-250 (140°F) | 300-500 (140°F) |
| Distillation (% by Vol. of Cut-back) | | | | | | |
| Off at 437°F. (%) | 12 | 10 | 9-12 | 10 | 2 | 2 |
| " " 600°F. | 25 | | | 25 | 10-20 | 8-20 |
| " " 680°F. | 40 | 30 | 30 | 50 | 27 | 25 |
| " " 600 to 680°F. | | 5 | 5 | | | |
| Pen. Res., 77°F. | 70-100 | 120-150 | 150-200 | 125-200 | 100-200 | 100-200 |
| Ductility, 77°F. | 100 | 100 | 100 | 100 | 100 | 100 |
| Sol. $CCl_4$ (%) | 99.5 | 99.5 | 99.5 | 99.5 | 99.5 | 99.5 |
| The material shall not be cracked. | | | | | | |

**In use prior to time Federal regulations were issued limiting specifications and types of asphalt to be manufactured.

Asphalt Institute Specifications

| Grade | RC-1 | RC-3 | MC-5 |
|---|---|---|---|
| Flash °F. | | 80+ | 150+ |
| Visc. (Furol) | 75-150 (122°F) | 250-500 (140°F) | 300-600 (180°F) |
| Distillation (% by Volume of Total Distillate) | | | |
| To 374°F. | 10+ | | |
| " 437°F. | 50+ | 25+ | 0 |
| " 500°F. | 70+ | 55+ | 20- |
| " 600°F. | 88+ | 83+ | 20-75 |
| Residue from Distillation to 680°F. | | | |
| Volume per cent by Difference | 60+ | 73+ | 82+ |
| Tests on Residue from Distillation | | | |
| Pen. 77°F., 100 g., 5 Sec. | 80-120 | 80-120 | 120-300 |
| Ductility 77°F.*** | 100+ | 100+ | 100+ |
| Sol., $CCl_4$ (%) | 99.5+ | 99.5+ | 99.5+ |

***Note. - If penetration of residue is more than 200 and its ductility at 77°F. is less than 100, the material will be acceptable if its ductility at 60°F. is 100+.

# TABLE 3

Values of (10 Mp) for Given Cut-back Boiling Point Intervals

| Boiling Point Intervals °F. | (10/Mp) |
|---|---|
| **Initial Cuts** | |
| 200 - 320 | .05 |
| 210 - 320 | .08 |
| 220 - 320 | .09 |
| 230 - 320 | .10 |
| 240 - 320 | .11 |
| 250 - 320 | .13 |
| 260 - 320 | .14 |
| 270 - 320 | .16 |
| 280 - 320 | .18 |
| 290 - 320 | .20 |
| 300 - 320 | .23 |
| 310 - 320 | .25 |
| 320 - 347 | .30 |
| 330 - 347 | .34 |
| 340 - 347 | .36 |
| 350 - 374 | .52 |
| 360 - 374 | .58 |
| 380 - 437 | 1.45 |
| 390 - 437 | 1.63 |
| 400 - 437 | 1.81 |
| 410 - 437 | 1.95 |
| 420 - 437 | 2.16 |
| 430 - 437 | 2.35 |
| 440 - 500 | 5.10 |
| 450 - 500 | 5.70 |
| 460 - 500 | 6.50 |
| 470 - 500 | 7.15 |
| 480 - 500 | 7.95 |
| 490 - 500 | 8.90 |

| Boiling Point Intervals °F. | (10/Mp) |
|---|---|
| **Intermediate Cuts** | |
| 320 - 347 | .30 |
| 347 - 374 | .51 |
| 374 - 437 | 1.30 |
| 437 - 500 | 4.46 |
| 500 - 600 | 26.00 |
| **Final Cuts** | |
| 437 - 450 | 2.90 |
| 437 - 460 | 3.25 |
| 437 - 470 | 3.39 |
| 437 - 480 | 3.57 |
| 437 - 490 | 3.97 |
| 437 - 500 | 4.46 |
| 500 - 510 | 11.10 |
| 500 - 520 | 12.20 |
| 500 - 530 | 13.30 |
| 500 - 540 | 13.80 |
| 500 - 550 | 15.60 |
| 500 - 560 | 17.20 |
| 500 - 570 | 19.40 |
| 500 - 580 | 21.70 |
| 500 - 590 | 24.10 |
| 500 - 600 | 26.00 |
| 600 - 610 | 91.00 |
| 600 - 620 | 106.00 |

p = Vapor Pressure read from Cox Chart

M = Estimated average molecular weight of hydrocarbons destilling off between given cut-back boiling points.

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