Cellulosic-covered electrodes have been used for circumferential shielded metal arc welding of line pipe over many decades. Unlike low hydrogen electrodes that achieve optimum results at low covering moisture levels, cellulosic-covered electrodes require much higher covering moisture levels for proper operation. Further, Johnson and Brace [1] recently suggested that high incidents of hydrogen assisted cracking (HAC) might be associated with low moisture levels in the cellulosic-covered electrodes used. This suggests further that storage and handling practices based on conventional wisdom in the field may not be sufficient as the industry transitions to more demanding applications and higher strength materials. Consequently, this work was undertaken to develop more definitive information on the performance of cellulosic-covered electrodes for three purposes:

• Determine the influence of storage and handling practices on covering moisture,
• Determine the influence of moisture on electrode operability, weld metal chemical composition and hardness
• Develop guidelines for cellulosic-covered electrode storage and handling.

Three different E8010 type electrodes were subjected to various storage temperatures and durations. As temperature increased, there was a tendency for lower electrode covering moisture levels with corresponding increases in weld metal alloy content, hardness, strength, and tendency for HAC. Variations in operation were also noted.

1. Background

A recent paper by M.Q. Johnson and W. A. Bruce [1] dealt with incidents of hydrogen-assisted cracking (HAC) in the welds of line pipe welded with cellulose-covered electrodes. This paper also discussed a number of topics related to the possible causes for the HAC in the girth welds. One of these topics was the effect of covering moisture on electrode operation and the resulting weld metal chemical composition and hardness. This led to questions about storage conditions and the effect on covering moisture for temperatures between room temperature (24°C (75°F)) and 86°C (186°F) as well as for different lengths of storage time.

Consequently, this work was undertaken to take a closer look at the effects of reduced moisture levels on cellulosic-covered electrode operation and weld performance. Some of these effects are known through practical experience. The changes in operating characteristics are a more globular metal transfer across the arc and a less forceful arc. These changes in welding characteristics were consistent for electrodes that have lower covering moisture content. A possible mechanism explaining the relationship between covering moisture content and arc force could be the very rapid, extreme change in volume as water changes from a liquid to a vapor. This rapid expansion might be causing metal droplets to travel faster creating more arc force. This rapid expansion could also be causing the molten metal to transfer across the arc as soon as it becomes molten which would result in a fine, spray droplet transfer. Conversely, lower moisture levels would have a lesser amount of vapor expanding which would lead to a lower arc force. It would also allow the molten droplets grow to a larger size before transferring across the arc, yielding a more globular droplet transfer.

Field practice supports this idea. It is common practice (although not recommended) for welders to improve the operability of dry electrodes by re-hydrating them in some manner. A few examples of re-hydrating techniques are:

• Leaving containers open to the atmosphere in a humid location.
• Wiping them with a damp rag.
• Dipping the electrodes in water.

The potential problem with re-hydrating dry electrodes in this manner is the lack of control over the amount of re-hydration that actually takes place.
2. Technical Approach

Three E8010 type electrodes with different designs (identified as Sample A (3/16 in. E8010-G), Sample B (5.0 mm E8010-P1), and Sample C (5.0 mm E8010-P1)) and manufactured by two different electrode manufacturers were utilized in this investigation.

The first objective of this investigation was to establish a correlation between covering moisture (as measured by % weight loss @ 149°C (300°F)) and storage condition.

Another objective is to evaluate the effect electrode covering moisture has on weld metal properties such as composition, strength, hardness, and cracking behavior. This evaluation was accomplished by welding simulated pipe joints (SPJ’s) with as-received electrodes as well as electrodes stored at 49°C (120°F) and 66°C (150°F) for the selected time period and comparing the weld metal properties. Weld metal cracking behavior was examined using the Gapped Bead-on-Plate (GBOP) test described by Graville [2], which was developed for evaluating the relative sensitivity to hydrogen cracking of weld metal.

An additional objective is to explain the differences in electrode operability. Comments and observations from the production welder were compiled during the test and correlated with moisture levels.

2.1 Initial Drying Curve Determination for Storage at 49°C (120°F) and 66°C (150°F)

Unopened containers of the three different cellulosic-covered electrodes were opened and sample electrodes were tested for covering moisture content. Electrodes were then removed from each of these containers, put on a rack and held at 49°C (120°F) for 7 days (168 hrs.). Samples were removed and tested for covering moisture after 1, 2, 3, 4, 8, 12, 16, 24, 48, 72, 96, and 168 hrs. in the oven. This test was repeated with another unopened container with the oven set at 66°C (150°F). The same oven was used for all storage tests above room temperature.

These results were plotted as covering moisture content vs. time at temperature. The resulting graphs allowed selection of a time at temperature where the rate of change in covering moisture level vs. time was minimal.

These tests showed that the majority of the moisture loss occurred within the first 48 hours at 49°C (120°F). At 66°C (150°F) the majority of the moisture loss occurred within the first 24 for all three electrodes. In both cases, the steady state moisture levels were not reached until about 110 – 150 hrs.

2.1.a. Follow Up Drying Curve Determination for Storage at 24°C (75°F), 38°C (100°F), 49°C (120°F) and 66°C (150°F)

The results of the initial drying curves at 49°C (120°F) raised questions about the effect of storage at temperatures between –40°C (-40°F) and 49°C (120°F). Since “ambient” up to 49°C (120°F) is considered a “safe” storage condition, further tests were conducted at room temperature (24°C (75°F)) and 38°C (100°F). For this testing, all three electrode designs were fully exposed as they were in the higher temperature storage tests. Since steady state covering moisture levels were achieved in a shorter length of time than the tests at higher temperatures, these two tests were conducted for only 72 hours.

The initial drying curve results also raised questions about the effect of storage condition on electrodes stored in containers as opposed to those laid out on racks. To test the effectiveness of this plus various can closures, drying curves for non-hermetically sealed material were compared to the original hermetically sealed package. Due to the number of test conditions, only Sample A electrode was included in this part of the follow up testing. The electrodes subjected to the follow up storage conditions have not yet been used for weld testing. Only the covering moisture content was tested for these electrodes. The additional re-sealing materials were: 1) duct tape (Duct), 2) masking tape (Masking), 3) cellophane packing tape (Packing), and 4) a shop rag held in place by a rubber band (Rag).

2.2 SPJ Welding for Properties, Test 1

For the first test (T1), each type of electrode was welded on simulated pipe joints (SPJ’s) made from 17 mm (0.685 in.) wall X70 pipe steel and having the joint configuration shown in Figure 1. Testing was conducted with electrodes in the as-received, stored at 49°C (120°F) for 48 hrs., and stored at 66°C (150°F) for 24 hrs. conditions. These welds were analyzed for weld deposit chemical composition and hardness. Any differences in welding operability were noted.

2.2.a SPJ Welding for Properties, Test 2

The first test was repeated to verify the initial test results and to check possible variation from one batch of electrodes (same design) to another batch. This second test (T2) was welded using different batches of electrode for all three electrode types. The second test added electrode storage at –40°C (-40°F) for 48 hrs. to the initial storage conditions and all weld metal tensile tests to the weld analyses.

2.2.b SPJ Welding Procedure and Joint Configuration
Welding was conducted in the vertical position with a downward progression at 170 – 180 amps DCEP using a 400 amp transformer welder. This simulated welding a pipe in the 3 o’clock position. All welding was performed in the same welding station, by the same operator.

2.3 Gapped Bead-On-Plate (GBOP) Tests

To exaggerate the cracking tendency due to HAC, a series of GBOP welds were made. This increased cracking tendency is accomplished by welding across an air gap, which acts as a fracture initiation site. This test permits comparisons of resistance to HAC tendencies, but only shows relative differences in cracking tendency. A variable used in this testing was the preheat temperature (the higher the preheat temperature, the lower the cracking tendency for a given electrode). The preheat used for this testing was 163°C (325°F). Results were measured and reported as a “percent cracking” for each test.

3. Results and Discussions

3.1 Drying Curves

Drying curves illustrated in Figures 2-5 show the effect of various storage conditions on electrode moisture content. Figures 2 and 3 illustrate that at 24°C (75°F) and 38°C (100°F), electrodes from Sample A and B are relatively immune to the storage condition. Sample C however, loses an appreciable amount of covering moisture at both these relatively low temperatures.

![Figure 2: Covering Moisture Content vs. Time Stored at 24°C (75°F), Follow Up Test](image)

![Figure 3: Covering Moisture Content vs. Time Stored at 38°C (100°F), Follow Up Test](image)

Figures 4 and 5 show that at 49°C (120°F) and 66°C (150°F) the drying behavior of Samples A, B, and C are similar. At 49°C (120°F) the moisture decreased from the “as received” condition to approximately 2.5% after 24 hours. At 66°C (150°F), the moisture decreased from the “as-received” condition to approximately 1.0% after 48 hours. These two storage conditions were used to establish relatively stable test conditions for assessment of welding characteristics and weld metal properties.

![Figure 4: Covered Moisture Content vs. Time Stored at 49°C (120°F), Initial Test](image)

![Figure 5: Covering Moisture Content vs. Time Stored at 66°C (150°F), Initial Test](image)

The drying curves shown in Figures 6 and 7 illustrate the effect various closing mechanisms have on electrode covering moisture during storage at 49°C (120°F) and 66°C (150°F). Although some closure mechanisms such as
plastic lids and tape slow down the drying rate, only hermetically sealed containers permit electrodes to maintain their original moisture content at these storage conditions.

![Covering Moisture Content vs. Time Stored at 49°C (120°F), Initial and Follow Up Tests for Sample A](image1)

![Covering Moisture Content vs. Time Stored at 66°C (150°F), Initial and Follow Up Tests](image2)

3.1.a Initial Test

Note that even though all of the electrodes start at different covering moisture levels, all three electrode designs have similar drying curves at 49°C (120°F), and almost identical drying curves at 66°C (150°F) after the first couple of hours.

Actual moisture equilibrium appears to occur between 100 and 150 hours at temperature. This was too long of a lead-time to schedule the welding with the stored electrodes. After 48 hrs. at 49°C (120°F) and 24 hrs at 66°C (150°F) the change in covering moisture content is considered sufficiently stable. Scheduling welding 24 and 48 hrs. in advance was much more manageable, which is the reason that these times were selected for preparing the stored electrodes for the welding comparison tests.

3.1.b Follow Up Test

Storing electrodes at 24°C (75°F) doesn’t necessarily cause a loss of covering moisture. Over 72 hours the covering moisture levels increased for Sample A, stayed relatively the same for Sample B, and decreased for Sample C. Also, while Samples A and B reached a similar equilibrium level, Sample C’s covering moisture level stayed at a higher level. This shows that each of these electrodes is trying to reach an individual equilibrium moisture with storage environment.

At 38°C (100°F) all three electrode designs reached approximately the same steady state covering moisture level after 24 hours. The covering moisture results for the first 8 hours showed increases for Samples A and B, which are not expected results and will need to be re-checked. During the first 8 hours, Sample C had the expected, steady decrease in covering moisture level.

Only the hermetically sealed cans protected electrodes from the loss of covering moisture. This was observed for both storage temperatures. A snap on plastic lid kept the loss of covering moisture to < 10%, which might be acceptable. The problem being, not all containers have snap on lids. The open can test with no lid results were comparable to the initial Sample A fully exposed electrode results when stored at 49°C (120°F). The same comparison for storage at 66°C (150°F) showed less agreement. After 168 hrs. Sample A electrodes had a reduction of 46% in covering moisture level in the follow up test (open can with no lid) and a reduction of 74% in covering moisture level in the initial test (fully exposed).

The various tapes used as sealing material in the follow up test all performed about the same with reductions in covering moisture levels of 20 – 25% after 168 hrs. This is not an acceptable reduction in covering moisture level. The shop rag did nothing to protect the electrodes, being equal in protection to that of the open can with no lid.

3.2 SPJ Test Results

Comparison of the differences among the three samples (Sample A, B, C) is a comparison of the differences in electrode designs. Comparison of the differences between the two tests within a sample (Test 1, 2) is a comparison of the differences from batch to batch within the same design. Different batches of the same electrode designs have different as-received covering moisture contents showing that there are natural variations occurring regardless of the design. Results of this comparison are shown in Table 1.
Table 1. Covering Moistures for the Electrode Used for the SPJ Welding Tests

The different designs had different starting covering moisture content but after storage at 66°C (150°F), they ended up with similar covering moisture content (within 15%). There was a lot more variation in covering moisture content design to design and batch to batch within a given design after the storage at 49°C (120°F). This greater variation at 49°C (120°F) may mean that the storage time at this temperature should be increased to limit the variation in future testing.

### 3.3 Electrode Operability

The welder observed a change in operating characteristics for all three electrodes when they were stored for 24 hours at 66°C (150°F) compared to the as-received electrodes. The arcs were softer and the metal transfer was more globular with electrodes stored at 66°C (150°F). Sample B also exhibited some longitudinal covering cracking when stored at 66°C (150°F). This was most likely due to the continued cross-linking of the silicate binder used for stick electrodes. As the cross-links form the covering contracts, putting it in tension. If a given design does not have enough silicate binder to form strong cross-links uniformly around the electrode, this increase in tension can cause a rift along a weak region forming the covering crack. All three electrodes showed an increase in tendency for porosity when stored at 66°C (150°F), although Sample B was the most affected. This increase in porosity is consistent with what is expected for dry electrodes. This could be due to lower levels of water vapor being created while welding, which helps to form a protective positive pressure barrier against the atmosphere.

The welder reported only slight changes in the operating characteristics for the electrodes stored for 48 hrs. at 49°C (120°F) compared to the as-received electrodes. The arcs were softer and the metal transfer was more globular with electrodes stored at 49°C (120°F), but not to the degree observed for the electrodes stored at 66°C (150°F). This altered operation varied from electrode to electrode, with some having operability comparable to the as-received electrodes.

No change in welding operating characteristics were observed for the electrodes stored at -40°C (-40°F)

### 3.3.a SPJ Weld Metal Properties

Weld metal mechanical performance corresponding with the reduction in electrode covering moisture levels is summarized in Figures 8 - 11.

Note that, though the covering drying curves were similar for all three electrode types, the SPJ weld test results differ among electrode designs. There was an increase in weld metal Ceq (Fig.8), hardness (Fig. 9), yield strength (Fig. 10), and tensile strength (Fig. 11) results with electrodes stored at 49°C (120°F) and 66°C (150°F) compared to those stored at room temperature or -40°C (-40°F). The magnitudes of these increases varied from design to design as well as from batch to batch within a given design. Sample A showed the largest increases in weld metal Ceq, hardness, and tensile properties.

<table>
<thead>
<tr>
<th>Storage Condition</th>
<th>Test 1</th>
<th>Test 2</th>
<th>Test 1</th>
<th>Test 2</th>
<th>Test 1</th>
<th>Test 2</th>
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<td>---</td>
<td>3.18</td>
<td>---</td>
<td>6.12</td>
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<td>3.38</td>
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<tr>
<td>Stored 24 hrs. @ 66° C (150°F)</td>
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<td>1.44</td>
<td>1.11</td>
<td>1.22</td>
<td>1.35</td>
<td>1.39</td>
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</tbody>
</table>

Figure 8: Weld Metal Carbon Equivalent (Ceq) vs. Electrode Storage Temperature

Figure 9: Weld Metal Hardness vs. Electrode Storage Temperature
3.4 Gapped Bead-On-Plate HAC Results
The GBOP test results shown in Figure 11 show that both Sample A and Sample C have a substantial increase in HAC comparing the electrodes stored at 150°F to those in the “as-received” condition. The increase in HAC for Sample B was much less than for the other two samples. This again shows that electrode design can limit the affects of electrode storage at higher temperatures.

4. Discussion
The increased susceptibility to weld metal HAC illustrated by the GBOP test results is consistent with changes observed in carbon equivalent, hardness, and strength. This can be explained by the differences in the metal droplet size transfer across the arc. Alloy contained in these droplets is subjected to oxidation as the droplet passes across the arc. This oxidation occurs on the surface of the droplets. As the droplet size increases, the ratio of the surface area (S.A.) of the droplet to the volume (V) of the droplet decreases.

\[ \text{S.A. of a sphere} = 4\pi r^2 \quad \text{V of a sphere} = 4\pi \frac{r^3}{3} \quad \frac{\text{S.A.}}{\text{V}} = \frac{3}{r} \]

The S.A. to V ratio for a unit volume of weld metal is inversely proportional to the radius of the droplet, so the ratio decreases at the same rate as the droplet radius increases. A lower S.A. to V ratio decreases the amount of alloy in the droplet that is in the position for oxidation (i.e. on the surface of the droplet), increasing the alloy content of the weld metal (most notably Mn, Si, Ti, and C). Even when the increase in droplet size is not noticeable to the eye, the alloy in the deposit will still increase, sometimes more dramatically than expected.

The increase in deposit alloy due to the decrease in covering moisture may also be explained by a shift in the water-gas reaction in the welding-arc atmosphere. The water-gas reaction is stated:

\[ \text{CO} + \text{H}_2\text{O} \rightarrow \text{CO}_2 + \text{H}_2 \]

If the moisture (H₂O) available is reduced, the water-gas reaction is driven to the left. This yields a higher concentration of CO in the arc atmosphere which makes it a more reducing, less oxidizing atmosphere. Less alloy would then be oxidized during the metal transfer across the arc, yielding more alloy in the deposit. The reducing affect of the shift in the water-gas reaction may be in part negated by the fact that less moisture changing from liquid to vapor during welding also reduces the amount of arc protection from atmospheric oxygen supplied by the water vapor formation.

The loss of arc force due to covering moisture loss causes another problem. Welders will often increase the amperage to regain the lost arc force. This higher amperage makes the weld puddle more fluid, adversely affecting the
stackability of a given electrode by causing the welder to weld with a faster travel speed in order to control the weld puddle. Loss of stackability will increase the number of passes required to fill the pipe joint (smaller weld size), which leads to a loss of productivity. Smaller passes result in a higher cooling rate that can lead to higher weld hardness. Increased puddle fluidity can also increase the amount of internal porosity, often not noticed until NDT testing of the weld conducted at a later time. This leads to costly repairs.

5. Conclusion

Storage of cellulosic-covered electrodes at elevated temperatures result in the following:
- Loss of covering moisture even after only a few hours.
- Moisture content of cellulosic-covered electrodes changing to attempt to reach an equilibrium with the environment.
- Increased weld metal carbon equivalent, hardness, tensile strength, yield strength, and HAC.
- Lower arc force and more globular metal transfer across the arc.
- Increased weld porosity.
- Possible covering cracking.

The most probable explanation for this is the decrease in the volume of gas vapor formed during welding when the moisture level of the covering of a cellulosic-covered electrode is reduced. Since water volume increases approximately 1600 times transforming from liquid to a vapor, there is a very high positive pressure at the arc. This high pressure causes the high arc force which in turn yields a finer spray transfer. The finer spray transfer allows more alloy to be oxidized during transfer across the arc, leading to lowered alloy in the deposit. The carbon equivalent, weld hardness, tensile strength, yield strength, and HAC are all at lower, more manageable levels with the lower deposit alloy level.

6. Recommendations for Further Investigations

- Do more testing with regard to re-sealing containers. Some of the loss in covering moisture may have been due to how often the container was re-opened. The various tapes may have lost some of their sealing ability due to repeated opening and closing.
- Determine at what storage temperature there are no adverse effects on welding operability and mechanical properties.
- Explore design changes that will retain covering moisture levels more effectively, even when exposed to higher than room temperature conditions.
- Explore whether electrodes can be designed and manufactured near the “equilibrium” moisture level, so that they are less subject to moisture variation.

7. References
