GENERAL ATOMICS

FERMILAB MU2E PS AND DS MAGNET PROGRAM

PROJECT 39532

TO:	Paul Clark, Neil Chitwood, Rick Hutsell Jonathan Miller, Sharon Davenport, Andrew Hearsum, Mark Myers, Pete Rinaldi	**DATE:**	July 19, 2019
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WBS:	N/A		
CONTRACT#	618313		
APPROVAL:	Paul Clark	**TECHNICAL:**	N/A
SUBJECT:	DS8 Winding Incident on June 28, 2019		
ATTACHMENTS:	N/A		

INTRODUCTION

This memo addresses the DS8 winding incident that occurred on June 28, 2019 and contains presentation slides that provide an overview of the incident, its root cause, the recommended corrective actions, and a risk analysis. The recovery plan is covered by the Rework Instructions in QN 7054611. A copy of the Rework Instructions are included at the end of this memo.

A copy of this memo shall be uploaded into the Windchill database in association with QN 7054611.

General Atomics Electromagnetic Systems Group

Title: DS8 Winding Incident, Root Cause, Corrective Action and Path Forward

July 19, 2019

Presented to: FNAL

Presented by: GA-EMS Mu2e Team

Background

- These slides addresses the DS8 winding incident that occurred on June 28, 2019
- QN7054611 has been written and signed off related to the incident
- High level details of the recovery plan are presented
- The successful execution of the recovery plan and risk mitigation activities will likely produce a useable coil.
- While currently identified as the DS8 coil, this coil will likely be reassigned as DS9 or DS10 that are less critical relative to DS8
- The recovery plan includes producing four conductor test samples that have been "exercised" through all the same plastic deformations that the actual cable experienced to date as well as the further deformations necessary to realized a finished coil

Background, continued

- If the recovered DS8 coil does not meet fabrication standards, (i.e. RRR, Al to SC bond strength, Ic) the coil may be reassigned to be a "spare" coil and only used in the event that one of the remaining 3 coils develops a more serious problem.
- Before the test samples can be supplied to Fermilab the winding machine needs to be cleared of conductor so that the test sample can be run through and experience the same deformations as the production cable
- After coil winding completion, the DS8 coil will be set aside for further instructions from Fermilab

Simulating the Deformed Conductor

- The S-bend area of the DS8 conductor shall be measured with a laser tracker to accurately document the shape
- Before performing any further action on the deformed section of DS8 a template shall be fabricated which shall be placed side by side to the actual deformed section for comparison and photographic record
- The survey data shall serve as a basis for the fabrication of the template
- The template shall be set aside for future fabrication of test samples

Simulating the Deformed Conductor, continued

- Four test samples that shall be fabricated to recreate the displacements, strains and cold work that the production DS8 conductor was exposed to in the area of interest
- The process used to straighten the production cable (in preparation for reversal through winding machine) shall be reproduced for the test samples
- The test samples shall be reversed and forwarded through the winding machine to simulate the actual processes of DS8

Fabrication of Test Samples

- At the conclusion of winding the DS8 coil approximately 66 meters of unused conductor remain from which four test samples shall be made
- Test samples shall be first formed and rolled onto the mandrel in the standard production process with the exception that the conductor will not be wrap insulated
- Test samples shall be manipulated/deformed by hand to represent the incident deformation (area of interest)
- The geometry of the simulated area shall be checked using the template

Fabrication of Test Samples, continued

- Test samples shall be straightened by hand to allow reversal through winding machine
- Test samples shall be reversed/backed up through the winding line to the straightening unit
- Test samples shall be forwarded and rewound onto the mandrel to the production DS8 radius
- The test samples shall have generous markings so that the dissection team can identify areas of interest
- The finished samples shall be removed from the machine, inspected to check radius, and shipped to Fermilab for testing

Complete DS8 Winding

- Prior to reversal of the deformed portion of DS8 through the winding machine all stations of the machine shall be thoroughly inspected and evaluated looking for any potential problems
- Special attention shall be paid to the wrapping heads to ensure they are not damaged or mis-aligned
- The DS8 deformed cable (area of interest) shall be straightened by hand to allow reversal through the winding machine
- The straightening process shall be documented with photos and/or video

Complete DS8 Winding, continued

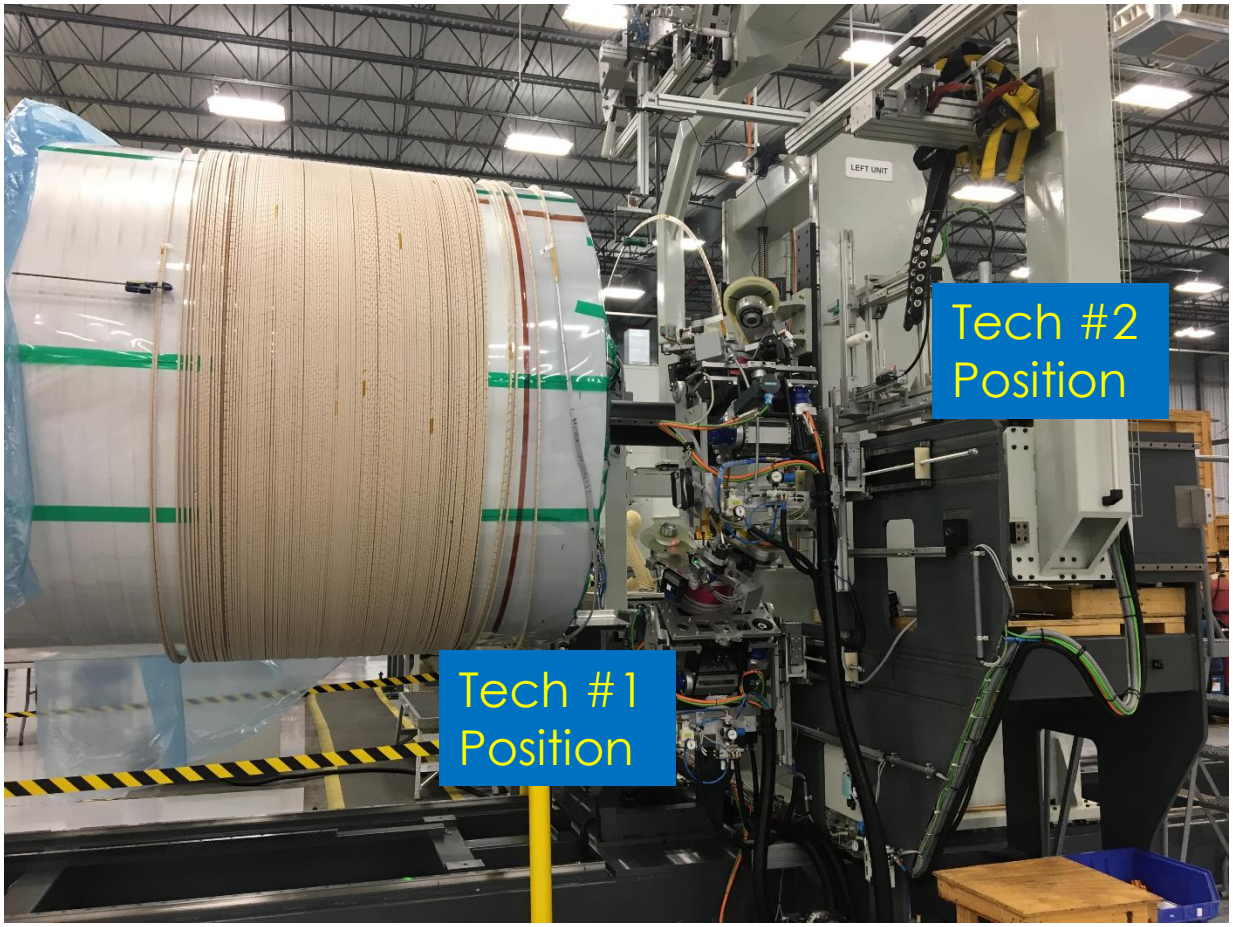
- The deformed portion shall be backed up to and through the straighteners up to the payoff spool
- Production winding shall be resumed
- At the start close attentions shall be given to the operation of the winding heads to confirm proper operation
- Upon exiting the straighteners the process shall be stopped and examined by engineering
- The area of interest shall be monitored and photographed at each step through the forward processes
- Permanent markings (visible from the outside) shall be made for future identification of area of interest

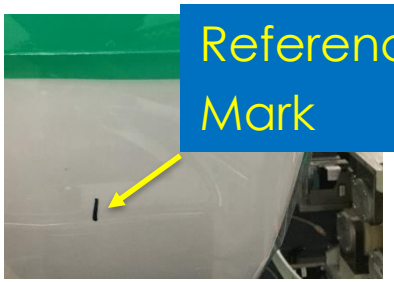
DS8 Winding Incident & Root Cause

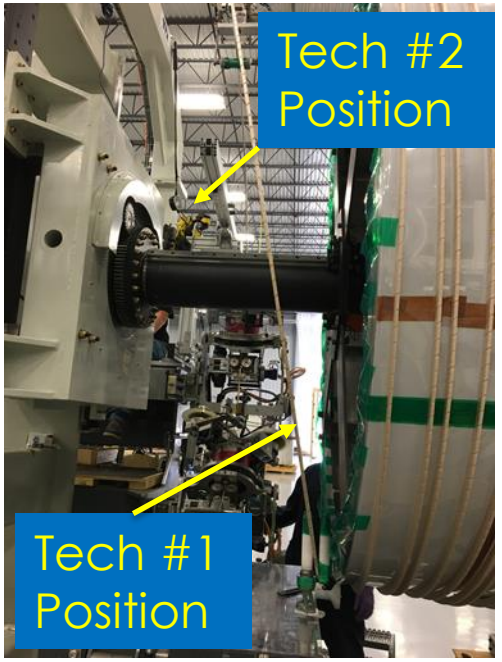
Mu2e Winding Standard Process (at time of incident)

- Technician #1 stands next to the wrapping heads to ensure that the conductor transitions smoothly onto the mandrel at the transition point. Technician has to manually migrate conductor horizontally to ensure that it is approximately 4-6 inches from the end of the mandrel as indicated by a reference mark on the mandrel O.D.
- Technician #2 stands up on the elevated platform and controls the mandrel speed with the “dancer”.
- Techs are instructed to stop (or call for the operator stop) the machine for any adjustments or if anomalies are observed.

Standard Process , Photos



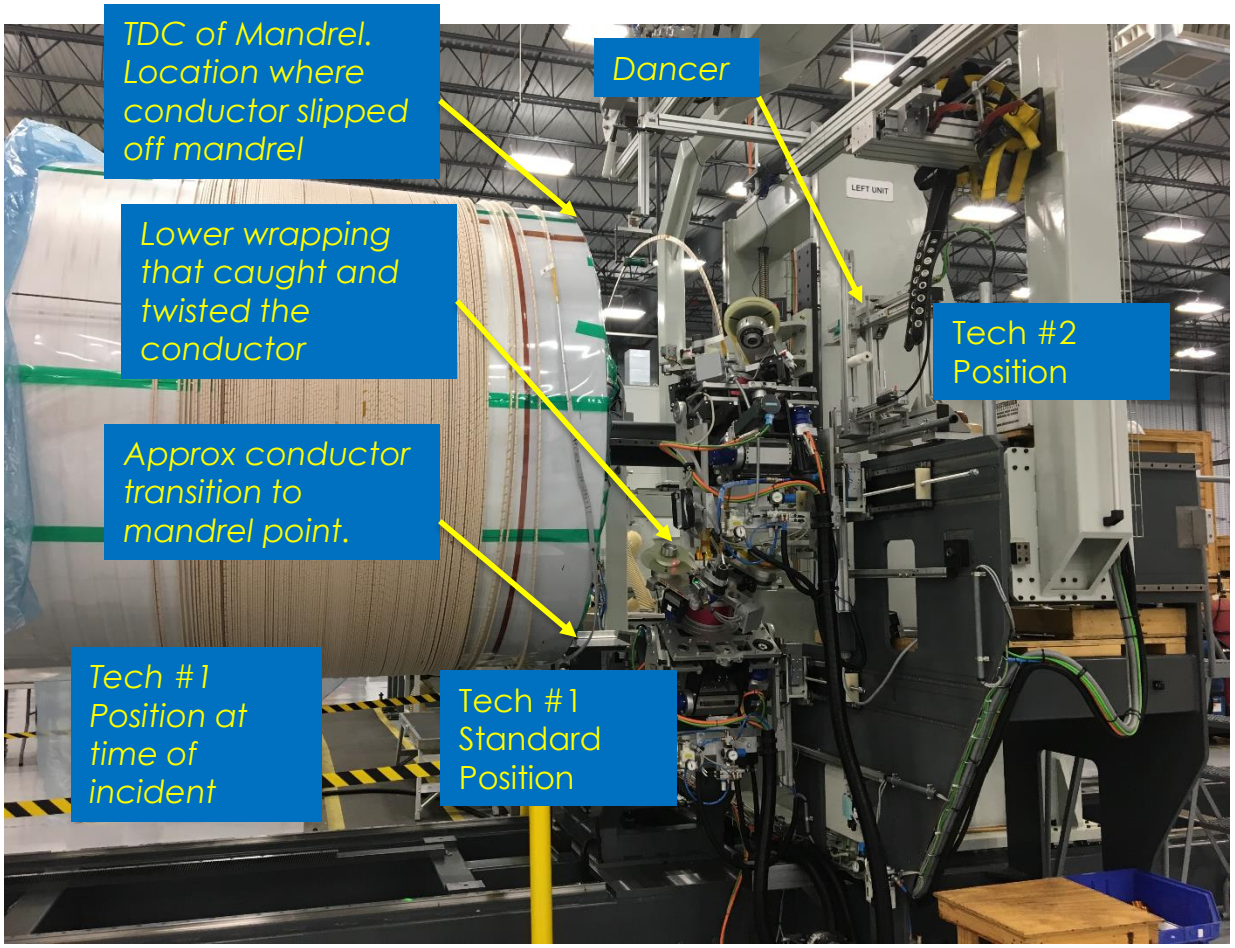


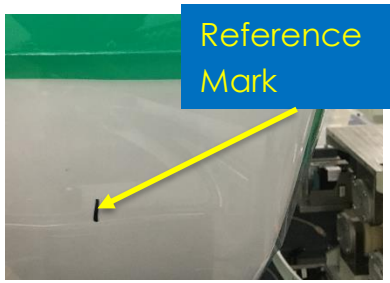


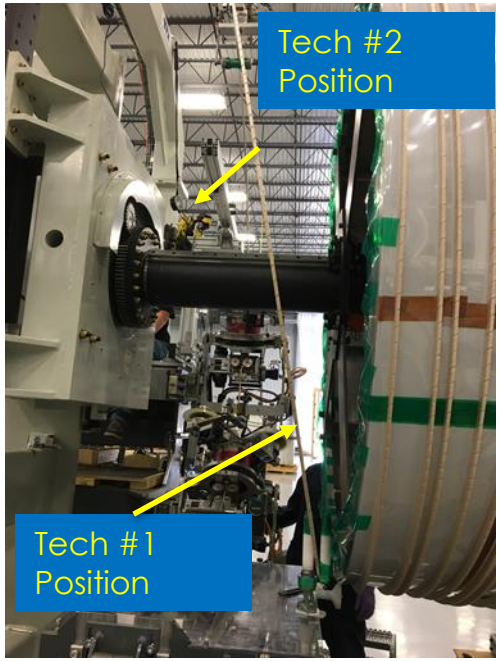
DS8 Winding Incident Description

- Technician #1 had briefly stepped 4 to 5 feet to the left of his normal position and was adjusting the conductor on the opposite end of the coil while the winder was still running.
- During this time, his attention was not on maintaining the 4-6 inch position of the conductor from the end of the mandrel.
- At the same time Tech #2 observed that the conductor had slipped off the end of the mandrel at TDC well past the transition point, causing it to become unstable.
- Tech #2 immediately called for the operator to stop the machine.
- The operator stopped the machine, but as the lower wrapping head was coasting to a stop it caught the unstable conductor and twisted it.
- The winding process was stopped immediately.

DS8 Winding Incident Description, Photos







DS8 Winding Incident Results

- **No one was injured from this incident.**
- **Twisted/bent Conductor**
  - Conductor was twisted 77 deg along a 9 ft section of conductor
    - 61% of the twist was on a 38 inch section.
  - S-Bend
  - There was also an "S-bend" that spanned 14 inches.
    - Radius of bends R18.3" and R14.0".
    - Measured by laser tracker.
- **Minor burrs**
  - No greater than 0.5 mm deep.
- **QN#: 7054611 was created to document this incident**

Root Cause

- **Man:** A technician continuously guides the conductor coil onto the mandrel as it is being wound, and keeps it at a predetermined distance from the edge. The technician stepped aside to push previously wound coil turns further back onto the mandrel, which involved taking eyes and hands off the mandrel edge (should have stopped the winder to take care of the other task). No job rotation for very monotonous post.
- **Material:** A change was made from PS conductor to the DS2 type, which forms differently.
- **Machine:** The winding head "caught" the coil while coasting to a stop & twisted it. May require a guard to keep things from falling into it.
- **Method:** Guiding the coils in place and away from the mandrel edge by hand. No engineering controls in place to prevent it from slipping off the top or becoming entangled in the winder in case of operator error.
- **Management:** Underestimated the magnitude of possible risks to the coil.
- **Measurement:** Winder speed was 25 mm/seconds. Time away from the edge of the mandrel was roughly 1-2 minutes. Time for the winding head to stop spinning after power off was roughly 3-5 seconds. The twisted section of conductor is about 9 feet long.

Corrective Action

Corrective Action Matrix

Category	Description	Corrective Actions
MAN	A technician continuously guides the conductor coil onto the mandrel as it is being wound, and keeps it at a predetermined distance from the edge. The technician stepped aside to push previously wound coil turns further back onto the mandrel, which involved taking eyes and hands off the mandrel edge (should have stopped the winder to take care of the other task). Adequate training is in question. Procedures which had been conveyed verbally & via hands on demonstration were not followed. The technician was observed continuously for a minimum of 4 hours before being allowed to take the post alone. Time on post and duration of shift were not evaluated. No job rotation for very monotonous post.	Write job descriptions/procedures for each of the four technician's posts at the winder and train the techs per these requirements. Establish technician competency requirements Implement a job rotation schedule for the four winding tech stations.
MATERIAL	A change was made from PS conductor to the DS2 type, which forms differently.	Ensure that pre-shift meetings cover any changes, safety, and potential risks for the day's tasks

Corrective Action Matrix, continued

Category	Description	Corrective Actions
MACHINE	The winding head "caught" the coil while coasting to a stop & twisted it. May require a guard to keep things from falling into it.	Add guarding around the lower wrapping head. Add another stop button near the Tech Station 2 position.
METHOD	Guiding the coils in place and away from the mandrel edge by hand. No engineering controls in place to prevent it from slipping off the top or becoming entangled in the winder in case of operator error.	Add a suspended roller (guard) near the top at the end of the mandrel to prevent the coil from slipping off. Increase the height of the coil retainer guides next to the mandrel.
MANAGEMENT	Underestimated the magnitude of possible risks to the coil.	Conduct a "What If" risk assessment on future Production Readiness Reviews and share these with FNAL.
MEASUREMENT	Winder speed was 25 mm/seconds. Time away from the edge of the mandrel was roughly 1-2 minutes. Time for the winding head to stop spinning after power off was roughly 3-5 seconds. The twisted section of conductor is about 9 feet long.	Same corrective action as in Machine section

Operator Expectations

- **For a right hand wind the Tech is to remain at the work station beside the wrapping heads to watch the conductor as it transitions to the mandrel. If the tech needs to leave his station for any reason, the machine must be stopped. Tech will manually assist and guide the conductor onto the mandrel as needed to ensure a smooth transition. Also, Tech will slide the conductor horizontally on the mandrel so it is 4-6 inches from the end of the mandrel as it rotates to TDC. If the tech observes any problems or anomalies he or she is to stop the machine by pressing the stop button.**
- **Potential Problems or anomalies:**
  - Damaged conductor insulation.
  - Conductor hitting the wrapping heads.
  - Conductor falls off mandrel
  - Conductor turns less than 4 inches from the end of the mandrel.
  - Conductor slipping out of guide rollers.
  - Incorrect Mandrel speed causing suspended helix turn not to form properly.
  - Damaged/bent conductor.
  - Unusual sounds from the machine.
  - Machine malfunction.
  - Any other anomalies that appear to cause a problem
- **Tech will monitor the wrapping of AWH 1 (Automatic wrapping head #1). The Kapton should be centered on the glass so that the glass insulation is always visible on both sides of the kapton. The machine will need to be stopped and wrapping head adjusted as needed to maintain this configuration.**

Risk Analysis

Risk Analysis, R1

- **The following risks and mitigation plans have been identified for the Path Forward on reuse/reforming of the DS8 coil**
- **For risk mitigation, conductor materials test are required**
- **Risk 1: Manipulation of the cable results in de-bond between cable and conduit.**
  - Mitigation: Fabricate a test article that has been "exercised" through all the same plastic deformations as the deformed portion of the conductor and provide the sample to Fermilab so that bond strength testing can be conducted and compared to baseline values

Risk Analysis, R2

- **Risk 2: Reforming of cable is not perfect and could lead to decrease in local packing density leading to undesirable variation in magnetic field.**
  - Mitigation: Backup the conductor far enough that the damaged conductor is run through both the horizontal and vertical straighteners. Upon resuming normal production – during manual compaction of the coil (that normally compacts 10 to 15 turns at a time) compact only two turns at a time just before and just after the problem zone for a total of three compactions of two cables at a time.

Risk Analysis, R3

- **Risk: 3 Reforming of cable is not perfect and could lead to imperfections of radius leading to local departure of cable from coil pack.**
  - Mitigation: Backup the conductor far enough that the damaged conductor is run through both the horizontal and vertical straighteners. Upon resuming normal production – examine the problem zone as it exits the upper winding head and lands on the mandrel. Check the problem zone for conformance to proper radius. During the compaction process, special attention shall be paid to the conductor area in question and extra effort shall be made to achieve the best mandrel fit-up possible.

Risk Analysis, R4, R5, R6

- **Risk 4: Nicks on surface of conductor damage insulation**
  - Mitigation: All nicks and burrs resulting from the incident shall be removed and sanded smooth to prevent damage to new wrap insulation
- **Risk 5: RRR of the aluminum is reduced in the re-worked area relative to the rest of the coil resulting in a hot spot in the case of a quench.**
  - Mitigation: Extract a sample of aluminum from the worst case cold working region of the test sample and send to lab to check RRR value
- **Risk 6: RRR value of copper is reduced in the re-worked area relative to the rest of the coil resulting in a hot spot in the case of a qench.**
  - Mitigation: Extract a sample of copper from the worst case cold working region of the test sample and send to lab to check RRR value

For this document, DS8 winding refers to the damaged DS coil presently on the winding machine on 7/19/19

QN7054611
REWORK INSTRUCTIONS:

1	Inspect all the stations before resuming any movement of the winding machine. Pay special attention to the wrapping heads to ensure that they are not damaged or mis-aligned.
2	Mark all areas of deformation with a marker to keep track of areas of interest. Transfer the markings to the OD of the insulated conductor so that the area of interest can be identified at *any* point in the future. They must ensure that the deformed sections of the production conductor can be identified after sand blasting, cleaning, re-forming and insulation.
3	Measure the deformed area of the DS8 winding with a Laser tracker. [The Laser tracker survey data of the “S bend” shall provide the basis for the conductor template that recreates the displacements.]
4	Fabricate a conductor template and place it side by side with actual the DS8 winding for comparison. Provide a photographic record of this. [The template will then be set aside for future usage]
5	Straighten the deformed section of the DS8 winding by hand to allow its reversal through the winding machine. Document this process with photos and/or video.
6	Using “soft” tools (tools with protected surfaces such as plastic of other “soft” materials), further straighten conductor on a “best effort” basis.
7	Starting with 200grit sandpaper, remove and sand smooth all nicks, burrs and scratches (to remove the deeper nicks). End by sanding with 400-grit sandpaper to remove scratches and to smooth out the work done with the 200-grit paper.
8	Install roller wheels on the three-roll bender that do not have a DS conductor groove* (in order to prevent damage to the grooves when backing up the conductor). *Grooved bender rollers will be replaced with "non- grooved" rollers *only* if the geometric shape of the conductor is deemed unable to pass through the grooved rollers (once it is reversed to this point)]. Position the Turks head back to the vertical position. Open all rollers on the wrapping heads as much as possible.
9	Return the deformed section (by backing up the machine) through all processes up to the payoff spool so the deformed portion of the conductor can be fed into the straighteners. [Make sure to remove the wrap insulation from the conductor prior to entry into the wrapping head when backing up.]

	STOP when the deformed section exits the straighteners. Have GA-EMS and Fermilab engineering representatives evaluate the condition of the recovered cable to determine if the process should be continued or if another action should be considered (such as running the deformed section through the straighteners a second time).
10	Resume Production winding: Return to the normal winding process (put grooved wheels back on three-roll bender if they were removed previously). Engage the wrapping head tapes where the old tape was terminated.
11	Monitor and photograph the area of interest at each step through the forward processes.
12	When the deformed portion of the cable exits the vertical straightener, stop and inspect the areas of the cable that had the worst deformation and document the results. Using a “straight edge” and “feeler” gages measure the straightness of the conductor on the narrow edge. Alternatively, the laser tracker can be used to measure actual radius. If radius is determined to be too small, consider backing conductor back through straightener again.
13	When the areas containing the worst deformation exit the washer, STOP and document the results. Verify that the S-bend area is still clearly marked. Then open the top covers of the washer and carefully visually track the S-bend area as it passes through the washer.
14	Transfer the markings on the conductor to the outside of the wrap insulation as it passes through the wrapping heads.
15	When the areas of deformation land on the mandrel, STOP and compare the geometry of the deformed areas to the geometry of neighboring conductors. Document the results.
16	When the winding is completed, set aside the DS8 coil on the mandrel for further instructions from Fermilab.
17	Fabricate four test samples (approximately 2 meters in length) for Fermilab testing, using the remnant conductor remaining on the DS8 winding reel.
18	Reproduce the approximately 1 meter deformed area using the previously set aside conductor template. Provide approximately 0.5 meter of undeformed cable at the beginning and 0.5 meter undeformed cable at the end to allow proper migration through the winding machine. The total sample length shall be 2 meters (minimum).
19	Using the winding machine, put the four test samples through the same procedure used to recover the DS8 winding.
20	GA-EMS and Fermilab engineering representatives will evaluate the quality of the recovered conductor as part of the final disposition of the DS8 coil. If the recovered DS8 coil does not meet fabrication standards, (i.e. RRR, Al to SC bond strength, Ic) the coil may be reassigned as a “spare” coil, only to be used in the event that one of the remaining three DS8 type coils develops a more serious problem.

	If the conductor is declared unfit for production usage, it shall be preserved and stored on a fixture that minimizes handling when transferring the coil from the mandrel onto the storage fixture. This storage method must ensure that the coil remains in a “ready to return to production” condition.

Verification of Rework:

Manufacturing Engineer:

_____
Print, Signature, Date

QA:_____

_____
Print, Signature, Date