SSC DETECTOR SOLENOID DESIGN NOTE #37

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MAGNETIC FIELD AND FORCE CALCULATIONS FOR AN SSC DETECTOR SOLENOID USING A COMMMERCIAL FINITE ELEMENT CODE

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ABSTRACT

The preliminary design of a large detector for the high energy physics program of the Superconducting Super Collider (SSC) is centered about a large superconducting solenoid magnet producing a field of 1.7 T over a volume 8 meters in diameter by 16 meters long. Reliability is emphasized due to the difficulty of performing any maintenance or replacement after installation. An important factor in determining reliability is the accuracy with which the solenoid field and electromagnetic forces can be calculated. The ANSYS general purpose finite element program, with 2-d and 3-d magnetostatic capabilites, was used to calculate magnetic field, Lorentz forces, and stored energy for the proposed solenoid geometry. Axial forces resulting from failure of individual coils were found to be much greater than those expected from initial axial offset of the solenoid from the magnetic center of the iron. Radial decentering forces were found to be negligible in comparison with the overall solenoid weight. Comparison of the 2-d and 3-d finite element results for field and forces in normal operation showed good agreement.

INTRODUCTION

The ANSYS general purpose finite element program has been used previously in the analysis of superconducting detector and accelerator magnets[1,2]. This paper will examine it's use in the 2-d and 3-d analysis of a proposed SSC large detector solenoid, with an emphasis on the effects of mesh refinement and iron characterization on the resulting forces for various normal and upset conditions.

MAGNETOSTATIC ANALYSIS WITH ANSYS

Magnetostatics belongs to a large class of engineering problems which respond to solution of the Laplace and Poisson equations for potential distribution. Heat conduction, seepage through porous media, and torsion of prismatic shafts are examples of other common problems of the same class. The finite element method is well established as a stable and accurate method of solving these problems.

2-d magnetostatics is solved by the vector potential approach in ANSYS[3], and is exactly analogous to 2-d heat conduction. The 3-d problem, however, presents special difficulties in a finite element solution, one of which is the three nodal degrees of freedom required by a vector potential formulation. To reduce the degrees of freedom and preserve the heat conduction analogy, ANSYS uses a reduced scalar potential formulation in which the field intensity H is calculated in two parts. The first part is due to source currents and is found from integration of the Biot-Savart law. The second part is the induced magnetization and is found from a finite element formulation.[3,4] This can lead to numerical cancellation problems when the induced magnetization and current source contributions are nearly equal, as occurs in highly permeable regions.

Lorentz forces on current sources and the Maxwell stress tensor forces on ferromagnetic regions are calculated from the field solution. In the 2-d case, ANSYS calculates and stores the Lorentz forces during the solution phase; These can then be listed directly during post-processing. The Maxwell stress tensor forces can be calculated by the user in the post-processing phase by defining a path through the air around a ferromagnetic region. ANSYS then performs the necessary integration to calculate the forces.

The calculation of forces in 3-d varies depending on the way in which the current sources are modeled. Standard source shapes such as bars, arcs, and coils can be input in terms of a few geometric parameters, which are then used for the Biot-Savart integration. The sources do not exist as finite elements, and the program does not calculate and store Lorentz forces for them. However, the user can perform the Lorentz force calculations using the post-processor and the field solution.

Complex 3-d source shapes may be modeled with finite elements which carry a specified current. The program calculates the Lorentz force on each element from the field solution and element current density. Regardless of source definition, forces on ferromagnetic regions can be calculated by a method of virtual work during the solution phase, and retrieved during post-processing.

Although ANSYS has recently added full 3-d vector potential and difference scalar potential elements, these were not available at the time this analysis was done.

THE PROPOSED SSC DETECTOR SOLENOID

An axisymmetric cross section of the proposed SSC detector solenoid is shown in Fig. 1 and consists of eight superconducting, pool-boiling coils, each 1.8 meters in magnetic length and 5 meters in radius. Four coils are assembled into an 8-m assembly, with the two assemblies independently supported in the magnet iron.

The magnet iron is octagonal in cross section, and includes endplugs which can, if necessary, be designed to extend into the bore of the outermost coils.

OBJECTIVES OF THE ANALYSIS

The objectives of the analysis were:

1. The correct current density for real iron to produce a central field of 1.7 T.

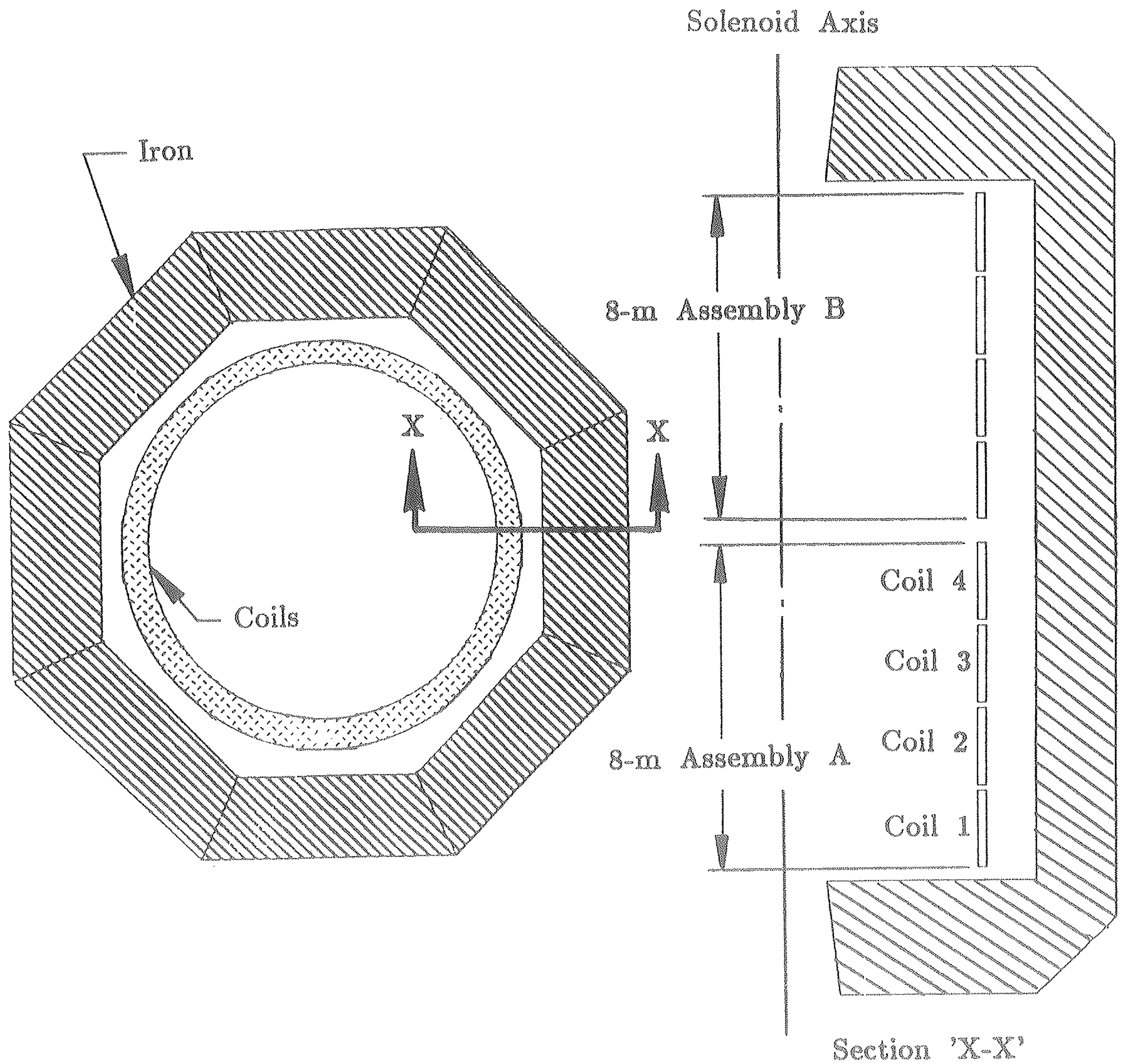

Fig. 1. SSC Detector Solenoid

2. The amount of endplug "re-entry" into the bore of the outermost coils to eliminate axial force for nominal assembly.

3. The decentering forces resulting from initial installation offsets of the solenoid from the magnetic center of the iron.

4. The maximum safe test current for single coil without iron.

5. The maximum stored energy and inductance.

6. The axial forces resulting from the failure of a single coil module and consideration of the possiblity of designing for operation with less than eight coils energized to full current.

7. Verification

TWO-DIMENSIONAL FINITE ELEMENT MODELS

All of the analysis objectives except the radial decentering force may be met with a 2-d axisymmetric finite element anslysis. A typical mesh is shown in Fig. 2. This mesh, using elements which are a maximum of 0.5 meters on a side, results in approximately 200 cp seconds/iteration

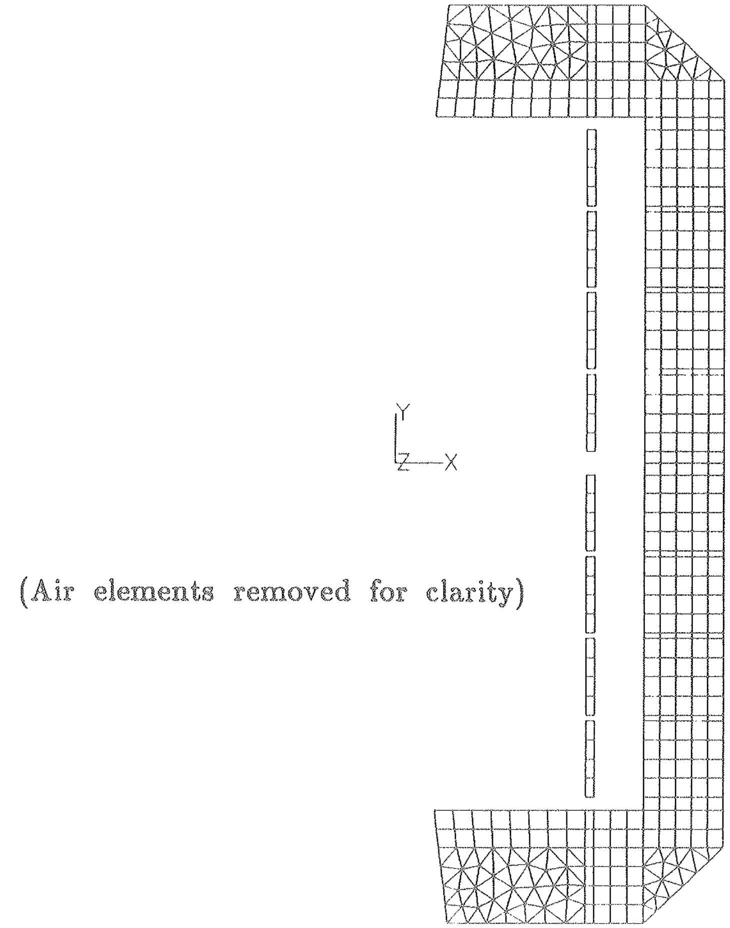

Fig. 2. 2-d Axisymmetric Finite Element Model

on a VAX3200 workstation. Up to 20 iterations were required by some runs to achieve convergence with real iron. The full model was necessary for coil failure and axial decentering analyses; during normal operation only one half of the solenoid need be modeled.

Operating current for 1.7 T central field. The current required for a central field of 1.7 Tesla was found for meshes with element sizes varying from 1 meter to 0.125 meters. Runs with infinitely permeable iron showed that the necessary current density was $7.3(10^6)\mathrm{A/m^2}$. For the proposed 616 turns of conductor in each coil, the superconductor operating current was 4560 amps. The central field varied by less than 0.1% over the range of element sizes considered. Later runs used a real B-H curve for typical 1020 magnet iron with both 0.5 and 0.25 meter element sizes, and the central field decreased by about 0.5% from the infinitely permeable iron results.

Re-entrant iron to minimize axial force. Results of runs with infinite iron permeability showed that the endplug iron should end approximately 0.3 meters outside of the bore of the outermost coil in order to minimize the axial force for a "perfectly" installed 8-m assembly. Refined models with real iron verified this result.

Axial decentering forces. These forces can result from installing the 8-m assemblies offset axially with respect to the magnetic center of the iron yoke. Five load cases were considered, using real iron and an element size of 0.5 meters. The results are summarized in Table 1. The maximum force was found for the case of a 25 mm displacement of each of the 8-m assemblies toward the center of the solenoid, and was 12400 kN.

Table 1. Axial Decentering Forces

	Load Case and Axial Offset	Force on 8-m assembly
1.	8-m assembly A: 25 mm	11600 kN
	8-m assembly B: nominal	10200 kN
2.	8-m assembly A: 25 mm	12400 kN
	8-m assembly B: 25 mm	12400 kN
3.	8-m assembly A: 25 mm	10700 kN
	8-m assembly B: -25 mm	4000 kN
4.	8-m assembly A: -25 mm	2700 kN
	8-m assembly B: -25 mm	2700 kN
5.	8-m assembly A: -25 mm	11600 kN
	8-m assembly B: nominal	8900 kN

Note: Positive offsets and forces are toward solenoid midplane

Maximum test current for coil. The coils will be tested without iron, and so will be subjected to large compressive forces. The maximum test current was established by finding the worst case operational compressive force, and calculating from a finite element model of a coil in air the current which will produce that force. In normal operation, the maximum force occurs in the coils at the ends of the solenoid, and is 13300 kN. A finite element model of a single coil shows that a current density of $1(10^6)$ A/m^2 gives a maximum coil force of 300 kN. Scaling this force gives a maximum test current density of $6.5(10^6)$ A/m^2, or 4060 amps.

Maximum stored energy and inductance. The stored energy from the two-dimensional models was calculated in the post-processing phase by performing a numerical integration over the volume of the conductor region of the product of the magnetic potential and the current density. The inductance can then be calculated from the stored energy and the total current. The stored energy for normal operation was found to be 1400 MJ, while the inductance was 112 H.

Axial forces due to coil failure. The coils may be individually energized, and the magnetic field and axial forces resulting from running the magnet with a failed coil were calculated. Fig. 3 shows the variation of the field with coil failure. Resulting axial forces are shown in Table 2. The maximum axial force of 54200 kN occurs on 8-m assembly A when coil 1 fails.

THREE-DIMENSIONAL FINITE ELEMENT MODELS

The calculation of the radial decentering force on an 8-m module assembly requires a 3-d finite element model of one-half of an 8-m assembly. (Fig. 4.) There are approximately 9000 nodes and elements, and one iteration of the model requires 6100 cp seconds on a VAX3200 workstation.

Radial Decentering Force. This force was found by displacing the coil centroids by 25 mm along the x-axis of the model. The coil elements were also displaced by 25 mm so that they were coincident with coil definitions. The virtual work option was used for force calculation. The results of the model showed that the radial decentering force resulting from a 25 mm offset from magnetic center was 200 kN.

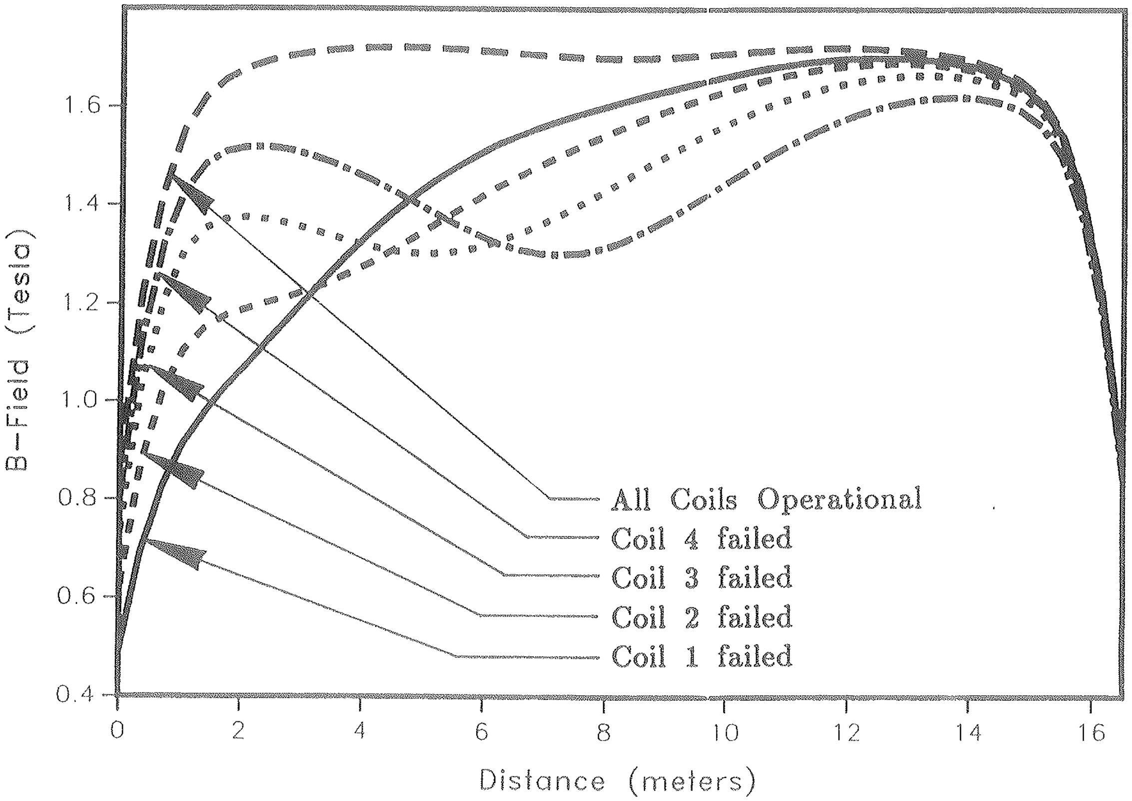

Fig. 3. Field on Solenoid Axis for Coil Failure Scenarios

Table 2. Maximum Axial Force on 8-m Assembly Due to Individual Coil Failure

	Model Characteristics		
Failed Module (see Fig. 1)	Inf. mu, 0.5 element size	Inf. mu, 0.25 element size	Real iron, 0.50 element size
Coil 1	54200 kN 8-m assembly A	54200 kN 8-m assembly A	53800 kN 8-m assembly A
Coil 2	23400 kN 8-m assembly A	23400 kN 8-m assembly A	23350 kN 8-m assembly A
Coil 3	-15300 kN 8-m assembly B	-15400 kN 8-m assembly B	-15000 kN 8-m assembly B
Coil 4	-37000 kN 8-m assembly B	-36900 kN 8-m assembly B	-36700 kN 8-m assembly B

Note: Positive force is toward solenoid midplane

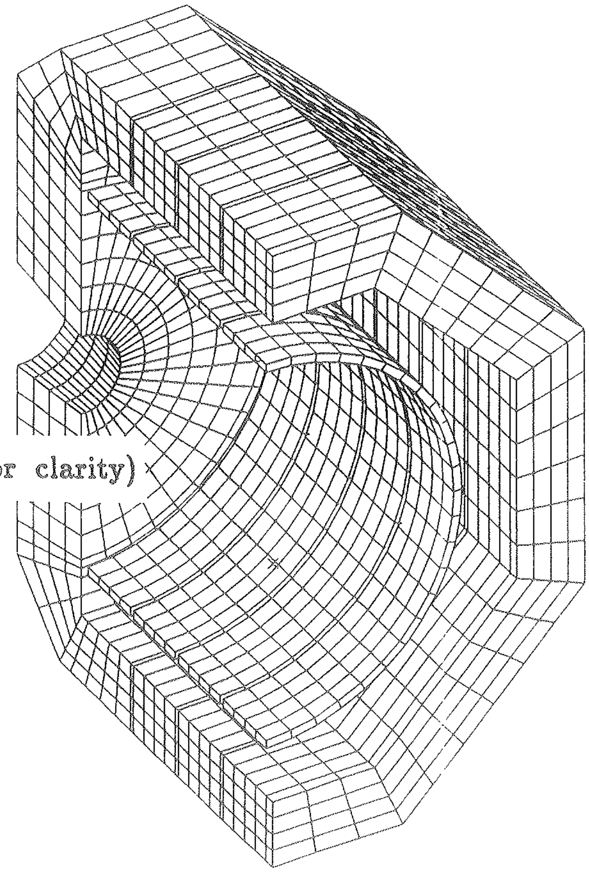

Fig. 4. 3-d Finite Element Model

VERIFICATION

Some analytical calculations can be made with which FEA results can be compared. For example, the original coil dimensions and currents were established by approximate hand calculations, and the FEA provided reasonable refinements of these for the present design. Stored energy, calculated by the assumption of uniform 1.7 T central field, is 1600 MJ, comparing with 1400 MJ from the FEA.

Another good indication of modeling accuracy is comparison of 2-d and 3-d FEA results for identical loadings.

<u>Comparison of 2-d and 3-d FEA results.</u> A 3-d model with 1/16th azimuthal symmetry was given the same current density as the 2-d model with infinitely permeable iron and an element size of 0.5 m. Fig. 5 shows the absolute difference of the axial field as calculated by the two models. Agreement was within 0.03 T at all points, and much better near the center of the solenoid.

The forces on the coils were extracted from the 3-d model through the post-processor by taking the cross product of the current density and the radial component of the B-field. These forces were compared with those from the 2-d model and found to agree to within 7% for all modules.

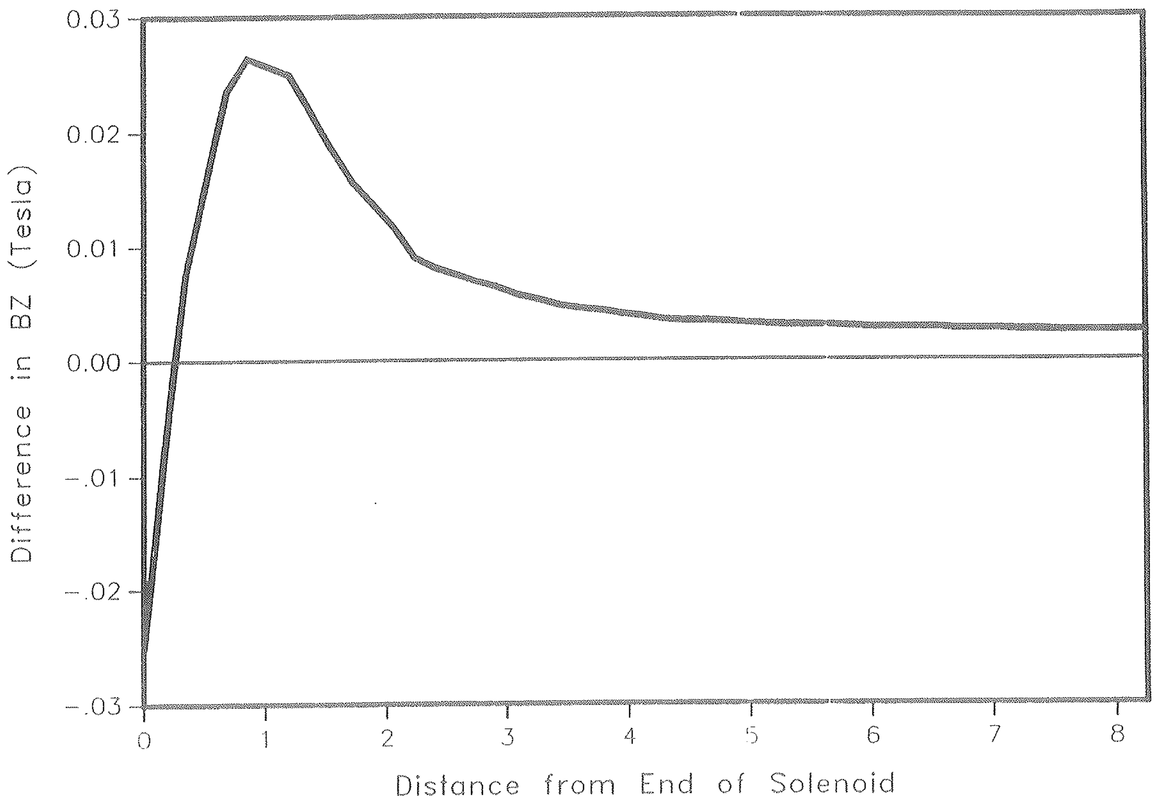

Fig. 5. Difference in Axial Field for 2-d and 3-d Models

CONCLUSION

The 2-d and 3-d magnetostatic analysis of the SSC solenoid was a straightforward application of the ANSYS program. The largest axial force of 54200 kN on an 8-m assembly was found for a coil module failure scenario. Radial decentering forces were negligible. These results canpes be used to establish the design forces for the 8-m assembly support systems.

ACKNOWLEDGEMENT

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