MASTER

THE DEALS MAGNET CONCEPT: APPLICATIONS AND DEVELOPMENT

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March 1977

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INFORMAL REPORT

DEPARTMENT OF APPLIED SCIENCE

BROOKHAVEN NATIONAL LABORATORY
ASSOCIATED UNIVERSITIES, INC.

Under Contract No. EY-76-C-02-0016 with the
UNITED STATES ENERGY RESEARCH AND DEVELOPMENT ADMINISTRATION

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ABSTRACT

The important highlight of the application of the DEALS (Demountable Externally Anchored Low Stress) magnet system to MFE Tokamak devices are presented in this report.* Benefits of the concept for the construction of superconducting toroidal field coils are outlined. Emphasis is placed on the application of DEALS to a high field collisional Tokamak device and various design parameters for such a device and the corresponding DEALS coils are listed. An engineering Tokamak of PLT size is described in which the DEALS concept could be thoroughly evaluated. Design parameters for two engineering Tokamak concepts are given. A proposed development program, whose aim is to evaluate and prove the DEALS idea and if successful, implement it as fast as possible in MFE designs is outlined.

* The unique design allowing demountability, and therefore relatively easy coil replacement, are explained.

I. INTRODUCTION - THE DEALS MAGNET CONCEPT

The "Demountable Externally Anchored Low Stress"[†] (DEALS) magnet system is a design concept in which coil segments, such as the units shown in Fig. 1, will be fabricated at a central factory facility. These segments can then be shipped to a reactor site and handled by present-day transportation systems and equipment. During the assembly process, each TF coil is formed from the basic coil segments. They are joined at the corners as shown in Fig. 2 such that the conductors in each segment are all connected in series in a spiral form. Consequently, this magnet coil construction scheme completely eliminates the on-site coil winding process previously proposed for the construction of MFE coils.

The important advantages of the DEALS magnet system are the following:

- (1) A malfunctioned coil segment can be replaced by a spare unit of corresponding length. The coil segment replacement operation will not disturb any other part of the reactor system and thus minimizes the required reactor down time.
- (2) Maximum accessibility is provided both during reactor construction and during reactor maintenance since all the outer vertical coil segments (or top horizontal coil segments) can be disengaged to provide the accessible working space as shown in Fig. 3. With the DEALS magnet system, it will be feasible to construct the blanket/shield assembly and associated neutral beam ducts, vacuum ports, fueling lines, etc, before the TF coil set is installed. This should result in large time and cost savings in reactor construction.
- (3) Because of the low stress and absence of tensile strain in the DEALS conductors, high field magnet systems using Nb_3Sn or other brittle superconductors should be capable of rapid development and application for magnetic fusion. A DEALS Nb_3Sn magnet set could be used for ITR/TNS reactors by the mid 80's.

[†]This idea of magnet construction was originated during a study of advanced fuels for Fusion Reactors which has been supported by EPRI.¹

On the other hand, in the conventional TF magnet system design with continuously wound D-shaped constant tension coils, the replacement of a failed coil after construction would be extremely difficult, if not impossible, which then requires that the TF coil system must be extremely reliable over its thirty-year service lifetime. Aside from the limited accessibility for reactor construction and maintenance because of the interlaced reactor components, the replacement of a failed TF coil in this type of reactor construction would involve removing and replacing a large number of highly radioactive, massive components with many major cuts and seals to be made. This means a very long plant down time, reduced plant availability, and large capital losses even if it were technically feasible. Fig. 4 illustrates how the TF coil reliability requirement depends on plant availability and replacement time. Conventional TF coils will have to be orders of magnitude more reliable than has been demonstrated to date if plant availability due to magnet repairs is to be above an acceptable limit of ~95%.

II. SUMMARY AND CONCLUSION

Based on the analyses in a previous report,² the potential benefits and penalties associated with this concept are summarized in Table II.1. The potential benefits are large as compared to the potential penalties which involve a somewhat greater refrigeration load and the necessity of using actively controlled movable magnet coil supports. However, the high field Tokamak TF magnet system conceived for the future, which is described in the later part of this report, will probably need similar supports as DEALS magnet system. We conclude that the DEALS magnet design concept appears to be the most practical and economical way for Tokamak reactor TF coil construction. Further study and experimental investigation should be carried out so that more detailed comparisons with conventional magnet designs can be made.

TABLE II.1 BENEFITS AND PENALTIES OF DEALS MAGNET SYSTEM

Benefits

- . Failed magnet segments can be readily replaced.
- . Reliability requirements on superconducting magnets do not have to be as stringent.
- . The magnet coil segments can be fabricated, mass-produced, and tested at a central factory and shipped to reactor sites. Field assembly work is much less than for conventional design superconducting magnets.
- . Stress in the conductor is significantly less than for conventional design superconducting magnets.
- . Reinforcement can be a PCRV or other warm structure, instead of more expensive cold reinforcement.
- . Coils can be non-planar and arranged to maximize radial and end access.
- . Tokamak reactor can be split at midplane for maximum access when replacing blankets.
- . Multiple plasma chambers can be used in one Tokamak TF coil system to reduce cost and share common subsystems (OH power supply, neutral beams, etc.).
- . Thick ceramic insulators can be used in the superconducting coil.
- . Brittle high field superconductors can be used at low strain levels. Advanced conductors prepared by non-conventional methods (sputtering, etc.) can be used.
- . Conductors can be shaped and placed to minimize pulsed field losses.
- . High conductor current minimizes energy extraction time in quench or accident situation.

Penalties

- . Greater refrigeration requirements (higher heat leak in leads and supports).
- . Movable supports required on perimeter of coils.

III. APPLICATION TO THE MIT COLLISIONAL TOKAMAK COMMERCIAL REACTOR

The MIT collisional Tokamak TF magnet system and its support structure is shown schematically in Fig. 5. The peak field in the conductor is 15 Tesla, while the field at plasma center is 8 Tesla. The physical dimensions of the system are also shown in the figure.

The application of the DEALS concept to this high field TF coil system is shown schematically in the same figure. The rectangular shaped broken-lined DEALS magnet matches the bore size of the collisional Tokamak magnet. The conductor is copper stabilized Nb_3Sn plate whose simple and straight forward fabrication process was described in a BNL report.² However, the conductor of the inner coil segment is a little more complicated since the cross-section of this segment is trapezoidal shaped as indicated in Fig. 6. In this figure one DEALS coil is shown with its approximate dimensions and in addition, joints are shown in a single turn. A better view of a corner joint is shown in the center diagram of Fig. 7. Some of the magnet parameters are shown in Table III.1.

In a conventional high field (15 Tesla peak field) TF magnet design, the constant tension principle is no longer applicable since the tension created by such a field will exceed the tensile strength of the conductor material. Therefore, a cold coil support structure is added as additional coil reinforcement as indicated in Fig. 5. In the DEALS magnet design concept, coil support is an essential feature of the system. It appears to be a potential penalty of this design concept at a lower field, but becomes less so when the required peak field goes beyond 10 Tesla, when compared with conventional high field TF coil designs. At the same time the flexibility of the DEALS coil support system design helps to reduce the stress in the coil since the low thermal conductivity support pads can be distributed so as to minimize stresses when this is done within a reasonable heat load range. Table III.2 gives the preliminary figures of the stress analysis

TABLE III.1**A DEMOUNTABLE, HIGH DENSITY, HIGH FIELD
TOKAMAK TF MAGNET SYSTEM PARAMETERS**

No. of coils	12
Coil bore	5.8m x 10.5m
Coil cross section (including 4-side insulation, each 1.0 cm thick) - inner coil segment	$\frac{(99.2 \text{ cm} + 151.7 \text{ cm}) \times 106 \text{ cm}}{2}$
Coil cross section (all other coil segments)	151.7 cm x 106 cm
No. of turns per coil	75
Conductor plate	Nb ₃ Sn with OFHC copper stabilizer as DEALS design
Insulation - Alumina	
(1) between coil turns	0.3 cm
(2) between coil and ground (coil case)	1.0 cm
Superconductor requirement at 15 Tesla (Nb ₃ Sn)	3 cm ²
Peak field at conductor (@ 3.04m)	14.8 Tesla
Field at plasma center (@5.6m)	8.04 Tesla
Operating current	2.5 x 10 ⁵ Amps
Amp-turn per coil	1.875 x 10 ⁷
Total Amp turns	2.25 x 10 ⁸
Average current density over conductor	1780 A/cm ²
Average current density over coil	1457 A/cm ²
Required heat transfer rate when all current flows in copper stabilizer	
(1) inner coil segment	0.3 watt/cm ²
(2) all other coil segment	0.24 watt/cm ²
Inductance per coil	0.14 henry
Total inductance	1.66 henry
Stored energy per coil	4.3 x 10 ⁹ joules
Total stored energy	5.2 x 10 ¹⁰ joules

TABLE III.2

MAXIMUM STRESSES IN COLLISIONAL TOKAMAK COIL WITH INSIDE LEG CONTINUOUSLY SUPPORTED AND 40% OF PERIMETER OF OUTER LEGS SUPPORTED.

	<u>Steel Case</u>	<u>Conductor</u>
Inside Vertical Leg	33 KSI ($2.275 \times 10^8 \text{N/m}^2$)	21 KSI ($1.45 \times 10^8 \text{N/m}^2$)
Horizontal Legs	30 KSI ($2.07 \times 10^8 \text{N/m}^2$)	11 KSI ($7.58 \times 10^7 \text{N/m}^2$)
Outside Vertical Leg	25 KSI ($1.72 \times 10^8 \text{N/m}^2$)	9.5 KSI ($6.55 \times 10^7 \text{N/m}^2$)

15 Tesla at Conductor

8 Tesla at Plasma Center

3 Inch Coil Case

with the highest stress in the conductor about 21 KSI. This was achieved by using 31 in-plane support pads (40% of the outer coil perimeter is supported) spread around the three outside coil segments. Further study to optimize the number of support pads and the stress is required.

A preliminary cost analysis of this DEALS high field TF magnet system was made. The basic material cost for the magnet system is on the order of 23.5 million dollars as indicated in Table III.3.A. The conductor and coil segments fabrication, including field assembly is assumed to be the same amount as the material cost. This brings the total system cost to be approximately 47 million. The following arguments will qualitatively justify this low cost figure as compared to other fusion magnet systems (such as PLT) or fission reactor construction.

- (1) The basic conductors are identical flat plates⁽²⁾ which can be mass-produced.
- (2) The coil segments are identical units (two different lengths). Each segment is made of stacked conductor plates and insulator plates contained in a steel box as shown in Fig. 1, and they can also be mass-produced.
- (3) The field assembly is reduced to joining the corners and welding the coil cases.

In view of the simple coil fabrication and assembly process described above, there is actually very little labor involved. In addition, quality control of each piece of conductor, insulator, and the coil segment can easily be applied to such a mass-production process, and initial in-plant tests can be performed. The quality control and in-plant tests may cost another 10 million dollars, which then brings the total for the finished TF magnet system to 57 million dollars.

A cost analysis was also made for a MULTIMAK TF magnet system⁽²⁾ in which three plasma chambers share the same TF coil set. The basic material cost is

TABLE III.3 BASIC MATERIAL COST ESTIMATE FOR A DEMOUNTABLE HIGH DENSITY, HIGH FIELD TOKAMAK TF MAGNET SYSTEM.

(A) Coil Bore Size 5.8m x 10.5m - matching MIT Collisional Tokamak

<u>Material</u>	<u>Total Amount</u> (10 ⁶ lb.)	<u>Base Price</u> (per lb.)	<u>Total Cost</u> (million dollars)
Copper	9.1	\$ 1.0	\$ 9.1
S.S	2.4	1.0	2.4
G 10	0.4	2.65	1.0
SC	0.17	65.0	<u>11.0</u>
Total			\$23.5

(B) Coil Bore Size 11m x 32m - MULTIMAK with extended coil segments to accommodate 3 plasma chambers.

Copper	25.0	\$ 1.0	\$25.0
S.S	6.6	1.0	6.6
G 10	1.1	2.65	2.9
SC	0.5	65.0	<u>32.5</u>
Total			\$67.0

Note: The scale factor 2.75 is based on the ratio of the circumference of a single coil (98 meters) of multimak with extended horizontal coil legs to that of a single coil of collisional Tokamak size DEALS magnet coil (35.6 meters).

shown in Table III.3.B. The total cost is 67 million and is less than three times that of the basic system indicated in Table III.3.A.

Note that the MULTIMAK TF magnet system is radially extended to gain access space between the vertical outer coil segments and, therefore, is more than three times bigger in size than the base system described in III.3.A since the ratio of the bore size of the two coils is 5.8.

IV. APPLICATION TO UWMAK-II COMMERCIAL REACTOR

A DEALS TF magnet sized similar to that for the UWMAK-II power reactor is shown schematically in Fig. 7. The center diagram shows a typical coil joint. The method of joining in this case is soldering. Another joining method such as multicontacts pressure joints, where soldering is not required, will be described in a future report. This method has been investigated by LASL for superconducting switching for METS systems, and has shown a great deal of promise for high current joints.

The application of the DEALS magnet system to UWMAK-II has been studied in more detail than both the collisional Tokamak previously described and the engineering Tokamak described in the following section. The latter two magnet systems will be described in more detail in a forthcoming BNL report. The model coil segments shown in Fig. 1 and the assembled model coil shown in Fig. 2 were made for the UWMAK-II system. Note that the size of the coil is much bigger than the MIT collisional Tokamak and is also bigger than the MULTIMAK (ratio of bore size is 1.4) although its height is less than that of the MULTIMAK coil. In this comparison the vertical bore size of the MULTIMAK is assumed to be three times the collisional Tokamak vertical bore size. In practice this is probably not needed and therefore will reduce its overall height even further.

A preliminary study of this system including NbTi/Cu conductor and coil segment design and fabrication, stress analyses, heat load calculation, support system design, coil segment installation and removal procedure, cryogenics, etc. were given in some detail in the first BNL report.⁽²⁾ It is because of this study that we are convinced of the importance, practicality, and cost and performance benefits of this magnet design concept, and that its application to the near-term high field fusion devices such as ITR/TNS and EPR could prove very important for magnetic confinement fusion research.

For reference, the magnet design parameters and the result of the stress analyses are given in Table IV.1 and IV.2. More information and details of this system are described in the BNL report⁽²⁾.

V. APPLICATIONS TO AN ENGINEERING TOKAMAK

Before applying the DEALS magnet concept to ITR/TNS and follow on MFE reactor systems, the DEALS concept should be tested at some smaller size, with the test probably involving a full TF magnet set. One way to do this could be the construction and test (including demountable tests) of a engineering Tokamak which would use Nb₃Sn conductor, to confine a plasma comparable in size to that of the PLT. Successful operation of this device would then allow one to proceed with a DEALS magnet for a ITR/TNS or other experimental MFE reactor.

Two versions of an Engineering Tokamak were designed. The first version was copper stabilized Nb₃Sn conductor aiming at a field of 5.8 Tesla at the plasma center. The peak field is 9.6 Tesla. The second version uses high purity aluminum stabilized Nb₃Sn conductor aiming at a field of 9.1 Tesla at the plasma center. The peak field is 15 Tesla. The system layout and physical dimensions are shown in Fig. 8. The magnet parameters of both systems are given in Table V.1 and V.2. Note that the conductor size, and therefore, the coil size of the two designs

TABLE IV.1DEALS MAGNET PARAMETERS
[UWMAK-II SIZE]

No. of Coils	24
Coil Size	20m x 30m
Coil Cross-Section (including 4-side insulation, each 2 cm thick)	0.785m x 1.04m
No. of Turns Per Coil	50
Conductor Sizes (SC and Copper)	(1) 0.01m x 1m x 30m (2) 0.01m x 1m x 20m
SC Sizes*(NbTi)	(1) 0.001m x 1m x 30m (2) 0.001m x 1m x 20m
Insulator Sizes **	(1) 0.005m x 1m x 30m (2) 0.005m x 1m x 20m
Peak Field at Conductor (@5.75m)	8.35 Tesla
Field at Plasma Center (@13.0m)	3.69 Tesla
Operating Current	2×10^5 amps
Amp-Turns Per Coil	10^7
Total Amp-Turns	2.4×10^8
Average Current Density Over Conductor	$2000\text{A}/\text{cm}^2$
Average Current Density Over Coil	$1300\text{A}/\text{cm}^2$
Required Heat Transfer Rate When All Current Flows in Copper Stabilizer	$\sim 0.2 \text{ watt}/\text{cm}^2$
Inductance Per Coil	~ 0.33 henry
Total Inductance	~ 7.9 henry
Stored Energy Per Coil	6.6×10^9 joules
Total Stored Energy	1.58×10^{11} joules
Average Pulsed Field Rate Over TF Coil	0.5 Tesla/sec.
Rise Time (or down-time)	1 second
Plasma Burn Time	1000 seconds
Estimated Heat Leaks (Eddy current, power lead, coil case supports, etc.)-Rm. temp. power requirement	16.62 Mw
Estimated Refrigeration Requirement-Rm. temp. power requirement	20 Mw
Total Conductor Length Per Coil	4800 m
Total Conductor Volume Per Coil	48 m^3

*SC cross-section calculated for highest field of 8.35 Tesla

**Approximate dimensions

TABLE IV.2

DEALS STRUCTURAL PARAMETERS

Coil Case Thickness	5 in.	12.7 cm.
Central Column Thickness	19.7 in.	50 cm.

Stresses in Coils and Supports

Horizontal Legs

No. of Intermediate Supports	10	
Max. Stress in Steel Case	14 ksi	$9.6 \times 10^7 \text{ N/m}^2$
Max. Stress in Conductor	10 ksi	$6.9 \times 10^8 \text{ N/m}^2$
Max. Stress in Supports	31 ksi	$2.1 \times 10^8 \text{ N/m}^2$

Outside Vertical Leg

No. of Intermediate Supports	11	
Max. Stress in Steel Case	12 ksi	$8.3 \times 10^7 \text{ N/m}^2$
Max. Stress in Conductor	6 ksi	$4.1 \times 10^7 \text{ N/m}^2$
Max. Stress in Supports	14 ksi	$9.6 \times 10^7 \text{ N/m}^2$

Inside Vertical Leg

Continuous Support Along Entire Length		
Max. Stress in Steel Case	6 ksi	$4.1 \times 10^7 \text{ N/m}^2$
Max. Stress in Conductor	4 ksi	$2.8 \times 10^7 \text{ N/m}^2$
Max. Stress in Support	6 ksi	$4.1 \times 10^7 \text{ N/m}^2$
50% of Length Supported		
Max. Stress in Steel Case	9 ksi	$6.2 \times 10^7 \text{ N/m}^2$
Max. Stress in Conductor	5 ksi	$3.4 \times 10^7 \text{ N/m}^2$
Max. Stress in Supports	11 ksi	$7.6 \times 10^7 \text{ N/m}^2$

TABLE V.1**DEMOUNTABLE, ENGINEERING TOKAMAK TF MAGNET SYSTEM PARAMETERS**

No. of coils	12
Coil bore	1.5 m x 3.0 m
Coil cross-section (including 4-side insulation, each 1.0 cm thick) - inner coil segment	$[(19.2 \text{ cm} + 47.95 \text{ cm}) \times 57 \text{ cm}]/2$
Coil cross-section (all other coil segments)	48 cm x 47.95 cm
No. of turns per coil	25
Conductor plate	Nb ₃ Sn with OFHC copper stabilization
Insulation - Alumina	
(1) between coil turns	0.3 cm
(2) between coil and ground (coil case)	1.0 cm
Superconductor (Nb ₃ Sn) requirement at 10 Tesla	0.7 cm ²
Peak field at conductor (@1.0 m)	9.6 Tesla
Field at plasma center (@1.65 m)	5.8 Tesla
Operating current	1.6×10^5 amp
Amp-turn per coil	4×10^6
Total Amp turns	4.8×10^7
Average current density over conductor	
(1) inner segment	2983 A/cm ²
(2) all other coil segments	2244 A/cm ²
Average current density over coil	
(1) inner segment	2281 A/cm ²
(2) all other coil segments	1880 A/cm ²
Required heat transfer when all current flows in copper stabilizer	
(1) inner coil segment	0.35 W/cm ²
(2) all other coil segments	0.31 W/cm ²
Inductance per coil	3.86 mh
Total inductance	46.3 mh
Stored energy per coil	4.94×10^7 Joules
Total stored energy	5.93×10^8 Joules

TABLE V.2**A DEMOUNTABLE, HIGH DENSITY, HIGH FIELD
ENGINEERING TOKAMAK TF MAGNET SYSTEM PARAMETERS**

No. of coils	12
Coil bore	1.5m x 3.0m
Coil cross section (including 4-side insulation, each 1.0 cm thick) - inner coil segment	$\frac{(19.2\text{cm} + 47.95\text{cm}) \times 57\text{cm}}{2}$
Coil cross section (all other coil segments)	48cm x 47.95cm
No. of turns per coil	25
Conductor plate	Nb ₃ Sn with pure Al stabilization (20% filler for thermal contraction compensation) encapsuled in copper casing
Insulation - Alumina	
(1) between coil turns	0.3cm
(2) between coil and ground (coil case)	1.0cm
Superconductor requirement at 15-Tesla (Nb ₃ Sn)	3cm ²
Peak field at conductor (@1.0m)	15 Tesla
Field at plasma center (@1.65m)	9.1 Tesla
Operating current	2.5×10^5 Amp
Amp-turn per coil	6.25×10^6
Total Amp turns	7.50×10^7
Average current density over conductor	4662 A/cm ²
Average current density over coil	3565 A/cm ²
Required heat transfer rate when all current flows in stabilizer	~ 0.3 Watt/cm ²
Inductance per coil	3.86 mh
Total inductance	46.3 mh
Stored energy per coil	1.2×10^8 joules
Total stored energy	1.44×10^9 joules

are identical. This engineering Tokamak TF coil system design has the following important implications:

- (1) The interchangeability and flexibility of the system design allows the TF coil system to be upgraded, raising the on-axis magnetic field from 5.8 Tesla to 9.1 Tesla by interchanging geometrically identical coil legs without disturbance to any other components of the system.
- (2) The idea of a single high field facility to permit successive phasing of TNS, EPR, and DEMO is very compatible with the DEALS magnet system. The flexibility of the DEALS concept allows support system, cryogenics, etc. to be designed for interchangeable coil systems of the above fusion devices, as well as permitting ready upgrading of the blanket/shield, neutral beam, etc. systems. The engineering Tokamak could then serve as a prototype for a TNS/EPR/DEMO single facility.
- (3) Although a 100-ton coil segment, 12 meters long, of collisional Tokamak size (MULTIMAK application) is well within the present day handling equipment range, aluminum stabilized conductor will help to further reduce the physical size and weight of the magnet coil and ease both cost and component handling. The engineering Tokamak could then easily serve as a test bed for the testing of advanced conductor options that could be advantageous for EPR/DEMO and subsequent reactors.

The preliminary stress analysis for the first version engineering Tokamak using copper stabilized conductors is given in Table V.3. The average stress of 17 KSI is achieved by low thermal conductivity support pads with 46% of the outside coil perimeter supported.

VI. PROJECTED DEVELOPMENT PROGRAM

A design study of a high field DEALS TF system for a Demo-Commercial compact Tokamak power reactor is proposed for the balance of FY 1977. This design study will help to assess the technical feasibility of the DEALS concept, project fabrication

TABLE V.3

MAXIMUM STRESSES IN ENGINEERING TOKAMAK COIL WITH INSIDE LEG CONTINUOUSLY SUPPORTED

46% of Outer Legs Supported

<u>Steel Case</u>		<u>Conductor</u>
Inside Vertical Leg	20 KSI ($1.17 \times 10^8 \text{ N/m}^2$)	14 KSI ($9.65 \times 10^7 \text{ N/m}^2$)
Horizontal Leg	52 KSI ($3.58 \times 10^8 \text{ N/m}^2$)	17 KSI ($1.17 \times 10^8 \text{ N/m}^2$)
Outside Vertical Leg	35 KSI ($2.41 \times 10^8 \text{ N/m}^2$)	13 KSI ($8.96 \times 10^7 \text{ N/m}^2$)

53% of Outer Legs Supported

Horizontal Leg	32 KSI ($2.21 \times 10^8 \text{ N/m}^2$)	11 KSI ($7.58 \times 10^7 \text{ N/m}^2$)
Outside Vertical Leg	18 KSI ($1.24 \times 10^8 \text{ N/m}^2$)	7 KSI ($4.83 \times 10^7 \text{ N/m}^2$)

61% of Outer Legs Supported

Horizontal Legs	20 KSI ($1.38 \times 10^8 \text{ N/m}^2$)	8 KSI ($5.52 \times 10^7 \text{ N/m}^2$)
Outside Vertical Leg	17 KSI ($1.17 \times 10^8 \text{ N/m}^2$)	8 KSI ($5.52 \times 10^7 \text{ N/m}^2$)

9.6 Tesla at Conductor

5.8 Tesla at Plasma Center

2 Inch Coil Case

and assembly costs, and evaluate potential savings in reactor construction and maintenance time and costs if the DEALS concept is used. In addition, the study will identify in more detail the necessary development steps. This study would be carried out jointly by BNL and Grumman Aerospace Corporation, with collaboration from PPPL on plasma engineering. The allocation of study tasks is shown in Table VI.1.

The projected program for the five years starting in FY 1978 is geared to the construction of a demonstration engineering Tokamak with a superconducting DEALS magnet system, which would produce a PLT size plasma at a somewhat higher field than PLT. The characteristics of such an engineering Tokamak are outlined earlier in this report. The realization of this program goal will require component development and prototype coil tests as shown in the accompanying program plan (Table VI.2).

The component development tasks are shown in Tables VI.3 through VI.6. Copper stabilized Nb_3Sn conductor can be used in the engineering Tokamak and follow on DEALS systems. Development of advanced aluminum stabilized Nb_3Sn conductors would result in smaller, lighter coil segments for DEALS magnet systems. In addition, such conductors would have a greater degree of cryostability than copper stabilized conductors.

Development of joints follows two approaches: soldered joints and multicontact pressure joints. The latter type appears more attractive, since they could be assembled and demounted without soldering, which probably would reduce handling time. The multicontact pressure joints would use techniques similar to those being developed by LASL for the high current superconducting switches in their magnetic energy storage system. These switches, which use a Multilam type of joint, have operated very successfully for hundreds of cycles at current densities a factor of 10 greater than those in DEALS magnets. Tests at field strengths appropriate

for DEALS designs, under pressure/contact time conditions expected in DEALS magnets, will be carried out.

Single and multiturn joint tests will be carried out, initially without superconductor, and later with it. Results on 1/3 scale tests of soldered joints and multicontact pressure joints will be evaluated, and the best approach will be selected for the test of a full scale single coil for the engineering Tokamak.

The development tasks for the support pads, hydraulic systems, and insulators are oriented towards obtaining information desired for design purposes. These measurements should be relatively straightforward.

A very important feature of the DEALS concept is that the results of small scale component tests should be readily applicable to the design of large DEALS magnets, and to a great extent, behavior of the various components can be decoupled. For example, the mechanical and thermal properties of the support pads can be tested on a small scale and then applied to any DEALS design. Joints can be tested independently from the rest of the coil, so that tests can be carried out more quickly and cheaply. In addition, results with smaller scale joints should be readily extrapolated to larger joints if maximum current density and stress levels are not markedly different.

This means that the DEALS concept can be rapidly tested and applied to the large scale magnet systems needed for fusion power reactors.

The program calls for a test of 1/3 scale prototype coil for the engineering Tokamak to be carried out in FY 1979. Several prototype coil segments will be fabricated, and different combinations assembled and demounted to demonstrate the inherent mass-production capability of DEALS.

The next stage will be the test of a single full scale (1.5 x 3 m) coil for the engineering Tokamak. This will be then followed by the assembly of a full set of 12 TF coils for the engineering Tokamak.

The cryogenic and conductor fabrication facilities at BNL are adequate to carry out the component development and tests in part II of the proposed program. The prototype magnet coil construction and test, as well as the construction and test of a single engineering Tokamak coil can also be carried out at BNL.

Grumman's capabilities in engineering design, fabrication, cost analysis, etc. will be very valuable in all phases of the proposed program, including component development, coil tests, and production. The Grumman mass-production and test facilities would be suitable for fabricating the complete TF coil set for the engineering Tokamak.

In conclusion, we believe that the rapid development of large high field magnet systems using Nb_3Sn conductor is very important to the magnetic fusion program, since it offers the greatest chance of achieving the goal of compact, low cost, ignited fusion power reactors in the 1980's. The DEALS magnet concept appears to be the most practical way of using Nb_3Sn conductors. A high field DEALS magnet system will operate at low stress and strain levels (compressive, which is desirable for Nb_3Sn); it can be fabricated relatively simply and cheaply, as compared to conventional wound coils; and it permits ready replacement of failed TF coils, as well as allowing easier construction of the reactor assembly of the blanket/shield, vacuum, and neutral beam heaters.

TABLE VI.1

ORGANIZATION AND COORDINATION OF PROGRAM EFFORT FOR FY 1977

TABLE VI.2

PROJECTED PROGRAM

FY

77 78 79 80 81 82 83

I. CONCEPTUAL REACTOR DESIGN WITH DEALS MAGNETS (conductor, joints, support system, stress analysis, cryogenics, cost, etc.)							
A. Demo-Commercial Tokamak Reactor	—						
B. Ignition Test Reactor		—					
C. Engineering Tokamak		—					
D. High Magnetic Field Tokamak Facility (TNS/EPR/DEMO)			—				
II. COMPONENT DEVELOPMENT AND TESTS							
A. Conductor		—	—	—	—	—	—
B. Joints		—	—	—	—	—	—
C. Magnet Coil Support System				—	—	—	—
1. Support pads (low thermal conductivity)		—	—				
2. Hydraulic Systems		—	—				
D. Insulators		—	—				
III. MAGNET COIL CONSTRUCTION AND TEST (power supply, cryogenics, support system, etc.)							
A. Single Coil Prototype			—				
B. Single Engineering Tokamak Coil			—	—			
IV. DETAILED DEALS REACTOR DESIGNS							
A. Engineering Tokamak			—	—			
B. ITR/TNS or High Field Tokamak Facility for TNS/EPR/DEMO			—	—	—		
V. ENGINEERING TOKAMAK CONSTRUCTION AND INITIAL TEST				—	—	—	—

TABLE VI.3

DEALS CONDUCTOR DEVELOPMENT

Copper Stabilized Conductors (For Engineering Tokamak And Follow-On Reactors)

- . Fabrication and Test of Copper Stabilized Nb_3Sn Conductor Using Present Braid Capability.
- . Development of Wide Braid Nb_3Sn Capability.
- . Fabrication and Test of Conductor With Wide Braid Nb_3Sn .
- . Conductor Cooling Channel Design and Test.

Advanced Conductors

- . Model Tests of Aluminum Stabilized Nb_3Sn Conductor.
- . Fabrication and Test of Aluminum Stabilized Conductor with Wide Braid Nb_3Sn .

Leads

- . High Current Leads for Engineering Tokamak.

TABLE IV.4

DEALS JOINT DEVELOPMENT

Soldered Joints (1/3 Scale)

- . Mechanical and Electrical Tests of Single Joints Under Simulated Loadings.
 - . Tests without superconductor (copper plates at r.t. and 80°K).
 - . Tests with Nb₃Sn superconductor (including assembly and disassembly).
- . Mechanical and Electrical Tests of Multiturn Joints Under Simulated Loadings.
 - . Tests without superconductor (copper plates at r.t. and 80°K).
 - . Tests with Nb₃Sn superconductor (including assembly and disassembly).

Multicontact Pressure Joints (1/3 Scale)

[Same Program as Above].

Full Scale Joints For Engineering Tokamak

- . Tests of Multiturn Full Scale Joints With Nb₃Sn [Either Soldered Joints or Multicontact Pressure Joints, Depending on Type Chosen for Engineering Tokamak].

TABLE VI.5

DEALS SUPPORT SYSTEM DEVELOPMENT

Low Conductivity Support Pads

- . Thermal Conductance Tests Under Load.
- . Mechanical Properties Tests Under Load (Stress-Strain Relationships, Stress-Strain Limits, Cycling Effects).

Hydraulic System

- . Design and Integration of Hydraulic System with Support Pads.

TABLE VI.6

DEALS INSULATOR DEVELOPMENT

- . Fabrication and Mechanical Tests of Ceramic Insulator.
- . Measurement of Electrical Breakdown Properties of DEALS Conductor-Insulator Assembly at 4°K.

FIGURE 2

ACCESSIBILITY FOR REACTOR CONSTRUCTION AND MAINTENANCE USING DEALS MAGNET CONCEPT

FIGURE 3

FIGURE 4 PLANT AVAILABILITY AS A FUNCTION OF TF COIL FAILURE PROBABILITY (DOWN TIME DUE TO OTHER CAUSES NOT INCLUDED)

FIGURE 5

(NOT TO SCALE)

COIL SIZE INCLUDES
CONDUCTOR AND INSULATION

FIGURE 6

FIGURE 7

A DEMOUNTABLE, HIGH DENSITY, HIGH FIELD
ENGINEERING TOKAMAK TF MAGNET SYSTEM
(PEAK FIELD - 15 TESLA)

FIGURE 8

REFERENCES

1. Advanced Fuel for Fusion Reactors. EPRI-RP/645-3
2. J. Powell, et. al., "DEALS: A Demountable Externally Anchored Low Stress Superconducting Magnet System for Fusion Reactors.", ENL Report No. 50616.