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FED MAGNET TESTING IN SUPPORT OF DEMO

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ABSTRACT

The question of what experiences can be gained from the operation of superconducting magnets in FED has been addressed. The objective of this study was the application of FED magnet experience to the design and operation of DEMO. It is noted that such observations must not interfere with the main function of FED as a integrated fusion reactor. The task was started by collecting information on the design and operational performance of superconducting magnets at different laboratories. The known cases of failure are listed and the predominant causes are identified. One of the specific problems in long term operation of magnets in a fusion reactor environment is the effect of gamma and neutron radiation on the insulators. The pulsed nature of plasma operation such as in FED may aggrevate this problem. The existing criteria and available data base are employed, in combination with predicted neutron and gamma dose rates at FED magnet position, to arrive at an estimate of time to failure in this reactor. A test plan for the FED magnets is proposed which is based on the known timetable for meeting FED objectives and the assumed operating modes of that reactor. Appropriate types of tests on the magnets for each phase of FED operation are described and summarized in a chart. The suggested tests include, among other things, verification of design requirements and monitoring the long-term changes due to radiation. A suggested part of the testing is the accelerated exposure of coupons of magnet materials in FED and in other irradiation facilities. These accelerated tests will provide early warning of magnet failure.

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1. INTRODUCTION

1.1 Objective

This task will specify the duration of long-term tests of the superconducting magnets on FED necessary to obtain conclusive reliability information. This performance testing must not interfere with the main function of FED as an integrated fusion reactor. A second goal of the task is to identify the useful information which could be extracted from the magnet operations of FED and later applied to the design and operation of DEMO.

1.2 Background

The plasma physics of tokamak fusion reactors dictates that the magnet system, particularly the Toroidal Field (TF) magnets, be intimately intertwined with the plasma chamber, first wall, blanket, and shield. The ohmic heating (OH) coils are in a location which makes repair or replacement very difficult. The equilibrium field (EF) coils are quite large, making their removal from the reactor time consuming. The high induced radioactivity in the stainless steel first wall and shield structure will require that all maintenance, including that on the magnets, be done remotely.

All of the above factors combine to require that the superconducting magnet systems for tokamak experiments and power reactors be extremely reliable and maintenance-free. In recognition of this fact, the Large Coil Program (LCP) has been established at Oak Ridge to provide a separate non-radioactive facility in which to verify and improve the performance of superconducting toroidal field magnets.

FED will differ from LCP in several important aspects. First, the size of the FED magnets will be approximately three times those in LCP. Secondly, the maximum field at the conductor in LCP is 8 T while FED could possibly have a 10 T maximum field for part of its lifetime. Thirdly, because of the presence of a high temperature plasma, FED will produce neutrons and gamma rays, resulting in radiation damage which will not occur in LCP. Finally, fluctuations in the magnetic field produced by the plasma will interact with the superconducting magnets, creating additional dynamic forces which could affect long-term magnet performance.

Thus, magnet testing in FED can incorporate effects not available in previous fusion facilities. On the other hand, testing in FED must not endanger the availability of the facility for other plasma physics and fusion engineering experiments. Therefore, the testing in FED should be limited to those tests which require the unique aspects of the FED facility or the long duration of FED operation.

1.3 Selected Approach

In order to benefit from existing experience, we telephoned and/or mailed questionaires to the principal designers of superconducting magnet facilities presently in routine operation. The questions dealt with the design philosophy, the available data base, and anaytical methods that these facilities have used. Startup experiences and operational problems were also questioned. Those persons contacted are listed in Section 3.1. A sample questionaire is appended to this report.

2. SUPERCONDUCTING MAGNET SYSTEMS IN FED/DEMO

2.1 Design of FED Magnet Set

The FED toroidal magnet system consists of ten coils and is designed to operate for 250,000 pulses with 3.6 Tesla at the plasma axis and 8 T peak field at the conductor. For an additional 25,000 pulses, the magnet system is to operate with 4.6 T at the plasma axis and a 10 T maximum at the conductor. The superconducting poloidal field coils operate with a peak field of 7 T.

Four conductor options have been investigated for the FED superconducting magnets. The first option has a NbTi conductor and pool boiling. This conductor will operate at 4.2 K when the peak field is 8 T. When 10 T operation is required, the magnet will be cooled with superfluid helium at 1.8 K.

The second option, which is the baseline design for the FED, uses a NbTi superconductor and forced convection cooling. This conductor will have a temperature of 4.5 K for 8 T operation and 3.1 K for 10 T operation.

The third option employs a NbTi/Nb_3Sn hybrid which is pool cooled. The Nb_3Sn conductor will be used in those locations where the field exceeds 8 T.

The fourth option uses two sets of concentric TF coils. The outer set contains one of the LCP-type conductors and will be used alone during 8 T operation. The inner set of coils will employ either resistive copper or the advanced superconductors being developed for the 12 T Program at LLNL. During 10 T operation, both sets of coils will be used.

The ohmic heating (OH) and poloidal field (PF) magnet set for FED consists of a central superconducting (NbTi) solenoid together with two normal copper rings and two superconducting (NbTi) ring coils. The normal coils are located within the bore of the TF coils and have mechanical joints for demounting. The superconducting ring coils are located outside the bore of the TF coils.

2.2 Comparison of FED and DEMO Magnet Designs

As currently conceived, the STARFIRE/DEMO9 design has eight TF coils, compred with ten TF coils for FED. The superconductor will be NbTi and pool boiling helium will be the coolant. The peak field at the conductor will be 10 T.

In order to provide access to the blanket and shield the major radius of the TF mid-outboard leg is 11.6 m in DEMO. In FED the major radius of the TF mid-outboard leg is 10 m.

3. EXPERIENCE WITH LARGE SUPERCONDUCTING MAGNET SETS

3.1 Performance of Existing Facilities

Operating experience with existing superconducting magnets can provide some insight into how DEMO can benefit from the long-term operation of FED. The failure rates seen in these facilities also begin to indicate the duration of FED testing necessary to provide useful data to DEMO.

Several scientists at various research institutes were contacted through phone conversations and written questionaires to gather recent practical experience in magnet design. The names of the institutes and the persons contacted are as follows:

- Stanford Linear Accelerator Center (SLAC), Stanford University, S. J. St. Lorant
- ISABELLE Program, Brookhaven National Laboratory, Per Dahl
- Lawrence Livermore National Laboratory, D. N. Cornish and others
- Large Coil Program Oak Ridge National Laboratory, P. N. Haubenreich and M. J. Lubell
- Fermi National Accelerator Laboratory (FNAL), Helen Edwards
- National Bureau of Standards, Boulder, Colorado, R. E. Schramm
- Francis Bitter National Magnet Laboratory, Richard J. Thome
- MHD Program, Argonne National Laboratory, Richard Smith

Most reported accidents involve burned magnet coils or leads, although there are a few cases in which the dewars were also damaged.[1] These accidents are briefly described below:

1. In some prototype magnets of FNAL and LBL, a quench was initiated by a local hot spot due to wire movement, vapor locks or inadequate heat transfer in magnet. A local hot spot in FNAL's 2.5 foot model energy doubler caused burned insulation and melted indium.

2. The power leads in the MIT's superconducting alternator were improperly supported. This caused a local hot spot which initiated a magnet quench and resulted in the burnout of the 50 mm length of the power leads. The heat generated due to this accident increased the temperature of helium and reduced its dielectric strength. This led to arcing between the coil and the dewar. This superconducting magnet is a 2.5 T coil and its stored energy is 90 kJ.

3. A quench was initiated in the SLAC's Rapid Cycling Bubble Chamber (RCBC) magnet by a local hot spot due to cooling channel blocked by the deformed insulators. About 150 mm of conductor varporized due to arcing.

3. In the NASA SUMMA magnet, 32 power leads are continuously monitored, but the overheated lead was not detected in time because of the inadequate instrumentation. The lead was damaged causing the section connected to this lead to be damaged. The NASA SUMMA magnet is an 8.8 T system and has 18 MJ of stored energy. During the first 1000 hours of operation this coil quenched 25 times.

4. The BNL 8° transport magnet failed because the overheated power lead melted the conductor wire which caused arcing between magnet and the ground. The transport magnet is a 4 T bending magnet system and has a stored energy of about 0.3 MJ. In the first 2500 hours of opeation, this magnet has quenched about 50 times.

5. Induced eddy currents damaged the magnet dewar at NASA Lewis Research Center. A copper getter pan was soldered to the bottom of a dewar in the vacuum space to hold charcoal powder. The force between the getter pan and magnet due to the induced eddy currents deformed the dewar.

6. The magnets for the ISABELLE accelerator at BNL have undergone significant design changes recently. A prototype magnet was wound and performed according to specifications. However, subsequent production magnets exhibited excessive training and could not attain the specified 5 T field. Investigation showed that the support of the windings at the magnet ends was insufficient and that the stability of the magnet was very sensitive to the pretension in both the conductor and the circumferential bands. The braided conductors were replaced with a cabled conductor and the magnets were wound with a higher prestress and better insulation. The new design also provides for better support of the conductors at the magnet's ends. The new design requires very little training to reach the operating field of 5 T at 4.5 K under pool boiling test conditions.

3.2 Predominant Causes of Failure

The available operating experience with superconducting magnets indicates that the predominant causes for early failure are improper structural support of the conductor and locally inadequate cooling of the winding. Improper support results in movement of the conductor as the field is increased and the resulting frictional heat input causes a growing normal zone. Inadequate cooling is the result of poorly designed coolant flow or changes in the coolant channel geometry due to conductor or insulator movement.

Power leads carrying high direct currents are designed to be cooled by helium gas, and if the cooling paths are partially plugged or if the gas flow is otherwise reduced or diverted, the leads can heat quickly and be damaged or destroyed in less than a minute. If the leads are not adequately supported, they may fracture during operation initiating electrical breakdown and arcing inside the magnets.

Instrumentation has also been a cause of early failure in that fault conditions are not detected or are incorrectly identified. Voltage taps have also been a cause of failure when they have caused shorts between turns in the magnet winding.

The important point about these early failures is that they are the result of design deficiencies and not the result of materials degradation over time. Such design deficiencies should be found during the first year of routine FED operation. The real benefits to DEMO from long-term FED operation are in following the effect of conductor, stabilizer and insulation degradation on continued magnet performance.

4. LONG-TERM FED OPERATION AND TESTING

4.1 Magnet Component Testing

The Fusion Engineering Device will subject the magnets to a different environment from that found in present test facilities. Specifically, the magnet components will operate under neutron and gamma radiation, higher magnetic fields and fluctuations in the poloidal field due to plasma instabilities. Individual effects can be simulated in present test facilities, but the combination of effects will first be encountered in the FED.

Estimates of Time to Failure Due to Radiation

Neutron and gamma radiation will affect the properties of various components of superconducting magnets in different ways and will generally produce damage which may lead to failure.

Van Konynenburg[5] has addressed the relative radiation sensitivity of insulators, stabilizers, and superconductors in a systematic manner. In the following we employ his suggested failure criteria to calculate the expected time to FED magnet failure on the basis of the estimated radiation field at the magnet position.

As mentioned by Van Konynenburg[5], the exact failure criteria for superconducting magnets in each reactor can be established only after optimal design of the radiation shield with consideration for the total costs of the superconducting magnet components and the shield. However, in the absence of any interaction among the designs of these separate items we employ the generral approximate failure criteria from Reference 5.

The failure criteria for different components of superconducting magnets are defined in terms of some acceptable fractional change (deterioration) in the critical properties of those components as a result of radiation. The properties and suggested maximum allowable changes are summarized in Table 1.

The Rates of Change of Properties with Radiation

Generally speaking, the data base for ascerting the rate of change of superconducting magnet components properties with neutron and gamma radiations is very inadequate, particularly for radiation effects at cryogenic temperatures (T≈5 K) and at high magnetic fields.

Van Konynenburg[5] presented the existing data in 1980. Table 2 is a summary of the representative data from that work.

The insulator deteriorations are estimate to occur at 10^9 rads of neutron and gamma rays for G-10, and 10^{10} rads of neutron and gamma rays for glass-filled polyimide.

We employ the failure criteria of Table 1 and the rates of property changes given in Table 2, in combination with the predicted neutron and gamma radiation intensities at the position of superconducting magnets in FED, to estimate the lifetime of the different magnet components.

According to Reference 10 there are two sets of predicted values of neutron flux and gamma doses at the magnet position in FED. Those are obtained with two different computational models. We choose the higher values of the two sets in order to obtain a conservative estimate of the time to failure.

The predicted radiation fields are:

Total neutron flux = 1.5×10^{14} n/m^2-s

Combined radiation does in G-10 = 4.1×10^6 Gray/3.5×10^7 full power seconds

The estimated time to failure of the magnet components due to radiation in the FED operating conditions are summarized in Table 3. These are based on the integrated effects of the pulsed radiation fields.

TABLE 1. FAILURE CRITERIA FOR RADIATION EFFECTS[a]

Component and Type	Critical Property	Suggesteed Limit of Acceptable Change	Remarks
Superconductor, Nb-Ti	Critical current	10% decrease between annealing periods	Slow changes with neutron fluence and complete recovery on annealing (Annealing once per year)
Superconductor, Nb_3Sn	Critical current	1% decrease for lifetime	No significant recovery with annealing. Rapid change with fluence
Stabilizers (general)	Resistivity	25% increase between annealing periods	At least 80% recovery on annealing
Insulator, organic (G-10) with fiber reinforcement	Compressive strength, perpendicular to laminate	20% decrease for lifetime	Mechanical requirements are more stringent than electrical
Insulators, inorganic	Swelling	0.1% increase in linear dimension for lifetime	No recovery

a. Condensed from the text by Van Konynenburg.[5]

TABLE 2. EXTENT OF PROPERTY CHANGES DUE TO NEUTRON RADIATION[a]

Material	Affected Property	Neutron Energy Range, MeV	Neutron fluence n/cm^2	Extent of change %	Remarks
Nb-Ti	Critical current	0.01 - 14.8	3×10^{18}	-10	B=2-5 Tesla
Nb-Ti	Critical current	0.01 - 14.8	6×10^{16}	0	B>6 Tesla

TABLE 2. (continued)

Material	Affected Property	Neutron Energy Range, MeV	Neutron fluence n/cm^2	Extent of change %	Remarks
Nb_3Sn	Critical current	0.035 - 13.5	4×10^{18}	-1	Recommended rate
Al-Stabilizer	Resistivity	0.035 - 13.5	1.32×10^{17}	25	T=4.5 K B=8 Tesla
Al-Stabilizer	Resistivity	0.035 - 13.5	1.67×10^{17}	25	T=4.5 K B=12 Tesla
Cu-Stabilizer	Resistivity	0.035 - 13.5	2.8×10^{17}	25	T=4.5 K B=8 Tesla
Cu-Stabilizer	Resistivity	0.035 - 13.5	3.8×10^{17}	25	T=4.5 K B=12 Tesla

a. Summarized from Van Konynenburg.[5]

TABLE 3. EXPECTED TIME TO FAILURE OF FED MAGNET COMPONENTS DUE TO IRRADIATION

Component	Type	Expected Time to Failure (Full Power Seconds)
Superconductor (First and second options)	NbTi	2.0×10^8
Superconductor (Third option)	$NbTi/Nb_3Sn$	2.67×10^8
Stabilizer	Copper	1.87×10^7
Insulator	G-10	6.6×10^6

Recent irradiation experiments at the INEL[11] have exposed samples of G-10 to gamma and neutron doses of 3.8×10^{11} rads and 2.8×10^{10} rads respectively. Subsequent fatigue testing at 77 K and 352 MPa for 10^4 to 10^5 cycles in compression indicated that the insulator retained adequate strength for compressive use in superconducting magnets.

4.2 Proposed Magnet Test Plan

The timetable for meeting FED objectives as estabished by the FEDC is shown in Figure 1.[7] Note that the first three years of operation consist of an integrated systems checkout, followed by two years of operation with hydrogen and deuterium plasmas. During this early, essentially non-radioactive, phase the integrated performance of the magnet system components will be demonstrated.

The assumed operating modes for the various stages of FED testing are shown in Figure 2.[8] During the first three years of operation, the machine will produce 65,000 pulses with peak toroidal fields (at the conductor) up to eight Tesla. It is during these 65,000 pulses in tritium-free operation that the component design and integration will be verified.

Our proposed schedule for long-term FED magnet testing is shown in Figure 3. The operational phases of the overall device as shown in Figure 1 are also shown as the top line in Figure 3.

The thermal and mechanical design of the conductor, leads, dewars and cryogenic system will, of course, be extensively tested before assembly in the FED facility. During the integrated systems checkout phase of FED operation the combined performance of the magnet system and its interactions with other components of the FED reactor will be intensively examined.

These tests will include verification of the design requirements for stability of the conductor against quench propagation, performance of the conductor and leads under slightly degraded cooling conditions and response of the magnets to upsets in other parts of the cryogenic system.

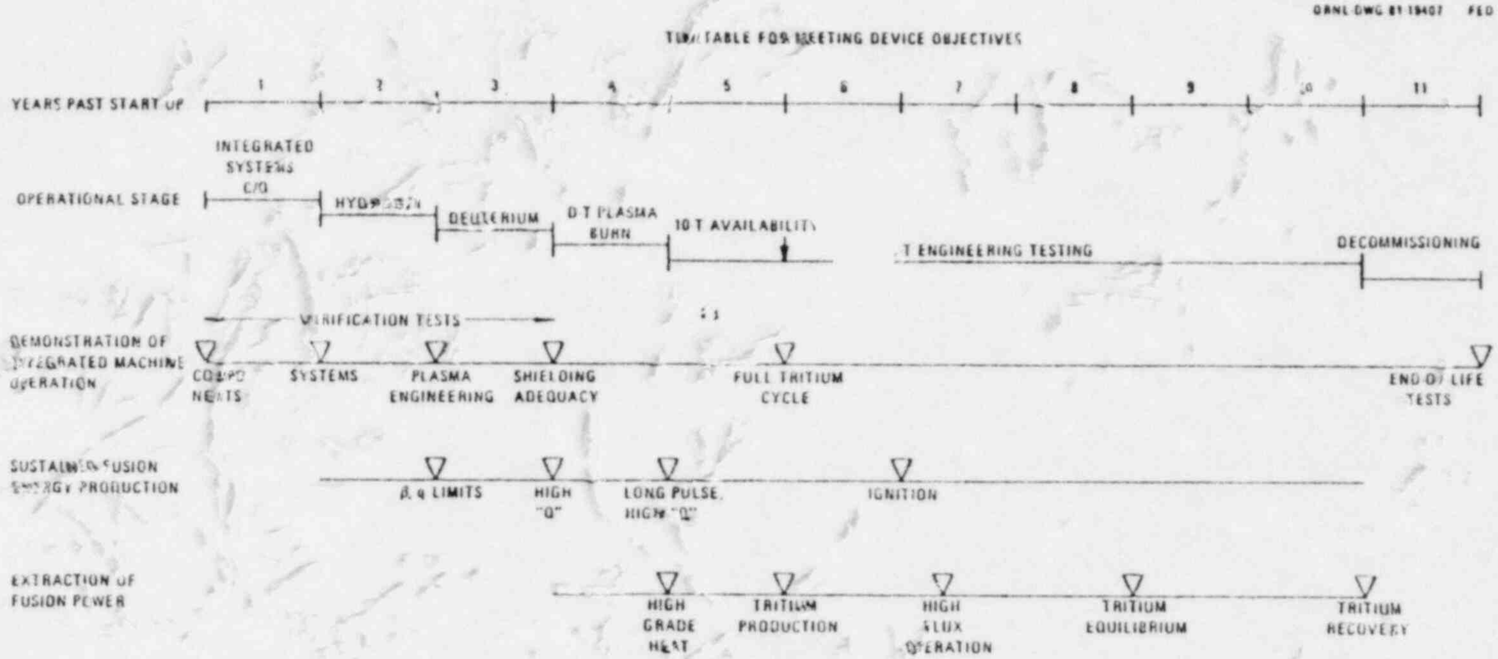


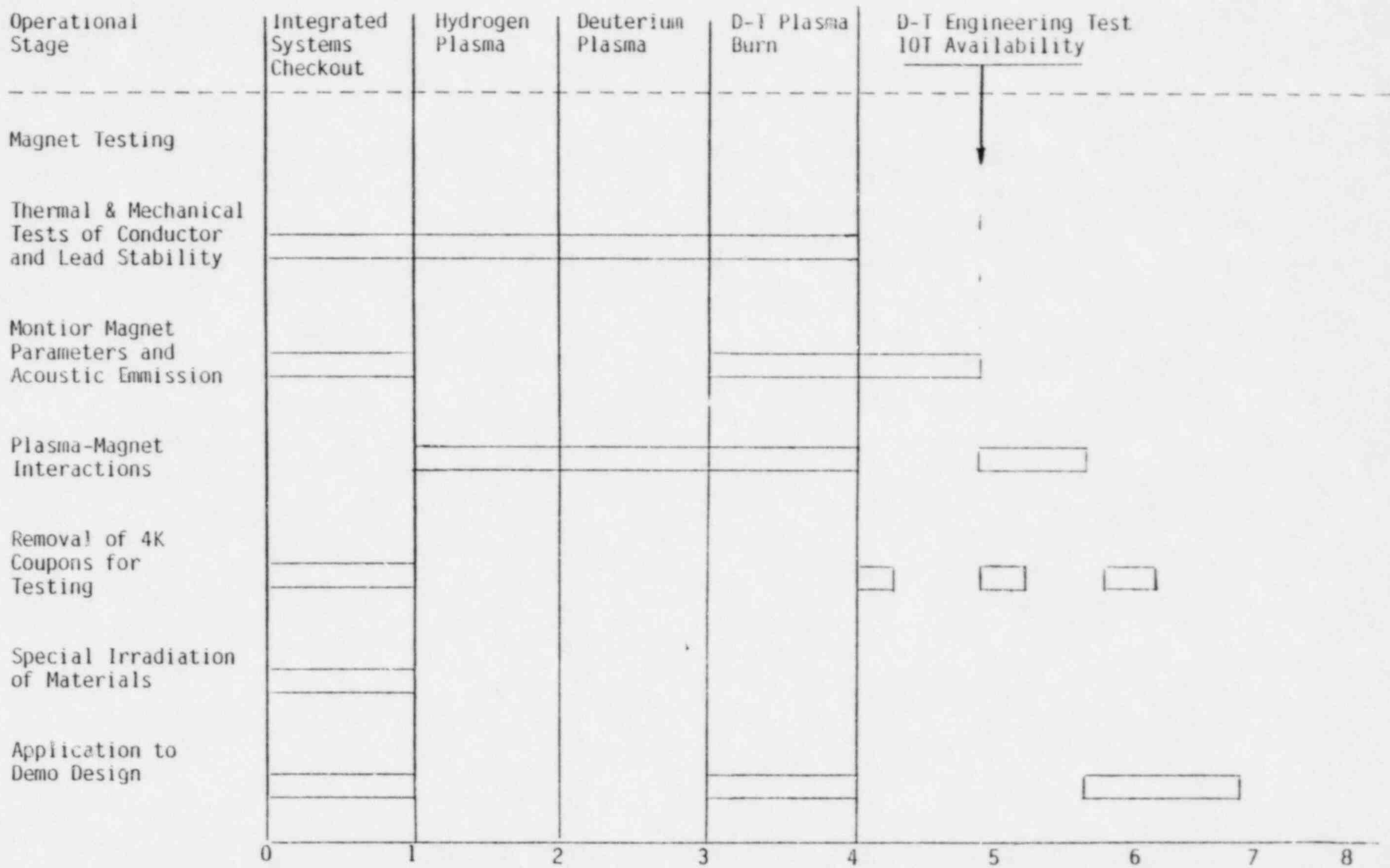
Figure 1. Timetable [Reproduced from Ref. 8]

OPERATING ASSUMPTIONS FOR THE VARIOUS STAGES OF DEVICE OPERATION*

Stage	Period (after startup)	Description	Peak Torodial Field	Operating Mode (on average)	Number of Pulses	Number of High Field Pulses 8 T	10 T
I	0-1.0	Integrated systems checkout	≤6 T (2/3) 8 T (1/3)	6 days/week 2 shifts/day 1 pulse/10 min Downtime of 2 weeks/month	15,000	5,000	--
II	1.0-3.0	Tritium-free operation	≤6 T (3/5) 8 T (2/5)	6 days/week 2 shifts/day 1 pulse/10 min Downtime of 1 week/month	50,000	20,000	--
III	3.0-4.0	D-T plasma burn	8 T	Same as Phase II	25,000	25,000	--
IV	4.0-10.0	D-T	8 T (8/9) 10 T (1/9)	Same as Phase II, except 1 pulse/ 5 min.	225,000	200,000	25,000
				Total	315,000	250,000	25,000

*Reproduced from Reference 7.

Figure 2.



PROPOSED FED MAGNET TESTING

Figure 3.

During the hydrogen, deuterium and D-T plasma phases of operation the thermal and mechanical testing will continue, albeit at a reduced level, in order to determine the response to plasma fluctuations and disruptions.

In order to monitor long-term changes in magnet performance as the result of radiation and large numbers of pulses, it is important to establish an "as installed" baseline before any inadvertant or planned overstressing has occurred. By carefully recording both the electrical characteristics and acoustic emissions of the magnet set during the integrated systems checkout phase, this baseline will be established. During hydrogen and deuterium plasma operation, data will be recorded. Since the potential usefulness of acoustic emission diagnostics may be compromised by the presence of a hot and turbulent plasma, the electrical and acoustic emission characteristics of the magnets will be thoroughly analyzed during the initial D-T plasma burn phase. The beginning of 10 Tesla operation will also be a time when the changed electrical and acoustic parameters of the magnets will need to be more closely scrutinized. During the remaining useful life of FED the parameters of the magnets will be continuously monitored, both as an indication of the long-term degradation of magnet materials, due to radiation damage, and as an indication of impending magnet failure.

The interactions between a hot plasma and a set of superconducting magnets will be seen for the first time in the Fusion Engineering Device. During the initial hydrogen and deuterium plasma pulses, the effects on the magnets of plasma fluctuations will be closely monitored. The introduction of a D-T plasma will increase the temperature and kinetic energy of the plasma about an order of magnitude, thus increasing the intensity of potential interactions. The beginning of 10 Tesla operation will increase the energy stored in the magnetic field by 50%, and will push the conductors closer to their stability limits. Analysis of the plasma-magnet interactions at the onset of each of these phases will indicate what effect the fluctuations in plasma current distribution have on superconductor stability and the fatigue life of organic insulators. During the remainder of FED's useful lifetime the magnets will be monitored for degradation and other trends in performance.

The most important long-term damage to the materials in FED will come from neutron and gamma radiation. To evaluate the changes in insulator and conductor properties during the reactor's lifetime coupons of those materials will be placed at various locations in the magnet and shield for removal at specified intervals. It is important that the coupons be irradiated at cryogenic temperatures and tested without first being heated to room temperature. Location of some of the coupons within the shield will allow for accelerated irradiation and the prediction of insulator and conductor performance over FED's lifetime. During the integrated systems checkout phase of FED operation coupons will be removed from the reactor in order to define baseline characteristics and in order to separate the effects of thermal and mechanical cycling from those due to radiation damage.

The coupons irradiated in the FED will serve primarily to confirm the irradiation studies done on identical materials previously in fission reactors. These fission reactor irradiations can be done concurrently with FED magnet design and aid in materials selection by the designers. As with the coupons installed in FED, the samples should be irradiated at cryogenic temperatures in fission reactors and tested without being warmed to room temperature.

In order to correlate fission reactor and FED irradiation results, careful dosimetry must be performed at the various coupon locations during the first D-T plasma burns. Computer code predictions for the radiation damage to insulators and conductors will be verified through comparison of coupons removed from FED with samples irradiated in fission reactors. Because higher fluxes are available in fission reactors, predictions for the end-of-life materials properties in FED or DEMO should then be possible.

The preliminary design of DEMO should begin about the time of the integrated FED systems checkout. During that first year the thermal and mechanical design of the FED magnets will be verified and designers can decide on its application to DEMO. Timely materials selection for the DEMO magnets will require that the irradiation rate be increased beyond that seen by the magnets in routine FED usage. This accelerated irradiation can be accomplished in fission reactors and at special purpose facilities such as FMIT and the Intense Pulsed Neutron Source. In addition, accelerated irradiation can be achieved in the FED by inserting cryogenic coupons of magnet materials at high flux locations in the shield.

Final materials selection can be made based on the condition of the first one or two sets of coupons removed from the FED after the beginning of D-T engineering testing.

4.3 Cryogenic System

Because of radiation heating in the magnets, the cryogenic systems for the FED will have larger capacities than in previous devices. In addition, the presence of gamma radiation may cause problems in the cryogenic system which supplies liquid nitrogen to the thermal shields surrounding the magnets.[12] Gamma rays radiolytically convert trace amounts of oxygen in the nitrogen stream to ozone. The ozone, in turn, can detonate when the temperature of the shield is raised above about 100 K. Continuous monitoring of the chemical constituents in the liquid nitorgen circuit will probably be needed.

Monitoring the impurities in the helium stream will also indicate whether radiolytic decomposition of the organic insulators is occurring.

4.4 Comments and Conclusions

The Fusion Engineering Device is to serve as a test bed for plasma physics and fusion engineering during the next two decades. Reliable operation of the superconducting magnets is vital to the accomplishment of that task. Therefore, any magnet testing done must not endanger the overall availability of the machine. Magnet testing should be limited to gathering operating experience and to monitoring the effects of radiation and plasma interactions on coil performance.

The behavior of materials in fusion magnets can be predicted based on the condition of coupons irradiated in the shield and coils of FED and samples of the same materials earlier irradiated in fission reactors at cryogenic temperatures.

Based on the proposed schedule for magnet testing and the accelerated irradiation of coupons, final design of the magnet systems for DEMO can begin during the first or second year of D-T engineering test in FED (see Figure 3).

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