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Preliminary Safety Assessment of the NET Magnet System

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Zusammenfassung

Vorläufige Sicherheitsbewertung des NET Magnetsystems

Im vorliegenden Bericht wird der Entwurf des NET/ITER Magnetsystems beschrieben, zusätzlich sind die bisher in supraleitenden Magneten aufgetretenen Fehler zusammengestellt. Vor diesem Hintergrund werden denkbare Störfälle diskutiert und sogenannte Referenzstörfälle abgeleitet. Das Inventar an Radioaktivität im Magnetsystem ist gering; es stellt sich aber die Frage, ob seine hohe gespeicherte Energie zu Störfällen führen kann, bei denen Radioaktivität-führende Systeme verletzt werden.

Von besonderer Bedeutung sind daher jene Ereignisse, die das Potential haben, sich vom Magnetsystem auf benachbarte Komponenten, die Radioaktivität umschließen, fortzupflanzen. Folgende Ereignisse werden in diesem Sinne als kritisch eingestuft:

(1) Unkontrolliertes Wachsen einer normal leitenden Zone, (2) Kurzschlüsse und Lichtbogen außerhalb und innerhalb einer Magnetspule, (3) Deformation oder Verschiebung einer Spule und (4) Volumenänderungen des Kältemittels Helium.

Der Hauptteil des Berichtes befaßt sich mit Analysen zu den Punkten (1) bis (3), d. h. konkret mit dem thermischen Versagensverhalten, dem Verhalten von Kurzschlüssen und Lichtbogen sowie den mechanischen Konsequenzen von elektrischen Fehlern.

Die bisher bei KfK durchgeführten Untersuchungen unterstreichen die Bedeutung von Quenchereignissen, von Kurzschlüssen und Lichtbogen sowie von mechanischen Reaktionen der Struktur des Magnetsystems.

Abstract

After a characterization of the magnet system for the conceptual design of ITER previous failures of superconducting magnets are briefly reviewed. Possible accidents are discussed leading to the definition of so-called reference accident sequences. Since the magnet system does not contain significant radioactivity inventories the large stored energies are considered mainly to have the potential to initiate or enhance accidents.

Of most concern are those events having a potential to propagate from the magnet system to adjacent radioactivity confining components. In this sense, the following events are considered to have a potential of failure propagation:

(1) Uncontrolled growing of a normal conduction zone, (2) shorts and arcs outside and inside a coil, (3) coil deformation or displacement, and (4) volume change of cryogenic helium.

The main part of the report deals with the assessment of items (1) to (3), this means in detail thermal failures, the behaviour of shorts and arcs, and the mechanical consequences of electrical faults.

The investigations performed up to now at KfK indicate the significance of quench phenomena, shorts-circuits and arcs, and the mechanical response of the structures.

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1. Introduction

Superconducting magnets for a fusion machine represent components with considerable requirements for advanced technology, high performance and reliability. The safe and reliable operation of the magnet system is an essential supposition for an appropriate availability and economic operation of the whole plant.

The magnet system may be subdivided into the following major subsystems:

- the toroidal field (TF) coils
- the poloidal field (PF) coils
- the supporting structures and cryostat
- the cryogenic system
- the TF and PF power supply and protection systems
- the coil services and diagnostics.

The main objective of this report is the investigation of conceivable magnet system failures.

Since the induced radioactivity in the coils is comparatively small the safety assessments of superconducting magnets point at the following questions:

Does the relatively large amount of stored energies within the superconducting magnets jeopardize the safe operation of the magnet system? Are there initiators and subsequent sequences of events which might lead to displacements or destruction of magnets and in consequence to a destruction of structures confining radioactivity?

Disturbances in the magnets such as a quench, a short or an arc may lead to heat production in the coil, to strong nonsymmetrical electromagnetic forces, and to a pressure rise in helium-filled conductors or containers. After detection of the disturbance the energy is usually dumped in external resistors. Safety relevant events are therefore those where this energy transfer is hindered or even made impossible. This is conceivable for various shorts and arcs arrangements within one coil or in the cryostat, or in the power supply/dump circuits.

When considering the status of the magnet design for NET and ITER the available references show that the most developed and consistent concept is the conceptual design of ITER. Hence, the database used in the following is that of ITER, and the considerations refer to the NET/ITER magnet system.

2. Characterization of the Magnet System

2.1 Functions of the Magnet

The NET/ITER magnet system comprises the TF coils and the PF coils and different additional sub-systems necessary for the safe and reliable operation of the system as a whole.

There are 16 superconducting TF coils in NET/ITER and three typs of PF coils:

- the central solenoid coils as the main transformer coils
- the outer PF ring coils
- the inner PF coils.

The TF coils produce ring shaped closed magnetic field lines keeping field ripple at the plasma edge below 2.5 %. In order to compensate field gradients and drifts of particles a poloidal magnetic field is superimposed leading to helical guiding magnetic field lines and allowing variations over a range of plasma parameters. The poloidal magnetic field is a combination of fields produced on one hand by ring coils concentric to the torus forming the primary winding of the Ohmic Heating (OH) transformer, and on the other hand by the plasma which acts as secondary winding of this transformer. The plasma current is induced by a unidirectional change of magnetic flux. The flux transient can be sustained only for a finite time, hence the PF coils have to be operated in a pulsed mode. Another function of the magnets is to purify and protect the plasma from impurities. By special shaping of the magnetic field a "last" closed magnetic surface is provided (called separatrix). The charged particles from the plasma having crossed the separatrix and impurities from the first wall within the edge-layer between separatrix and first wall may be exhausted by the divertor system.

In conclusion, the main functions of the magnets are the following:

- to heat the plasma
- to confine the plasma
- to control plasma current
- to position the plasma
- to shape the plasma and provide a divertor field.

With the exception of the inner PF coil the magnets are superconducting. To establish the superconducting state, thermal insulation and cooling are important auxiliary functions.

2.2 Design Boundary Conditions and Design Data Base

TF and PF coils with the associated support structure are contained by the cryostat. The cryostat forms the first barrier against release of radioactivity from the magnet systems caused by a severe magnet failure including arcing induced material vaporization.The design value for an internal accidental overpressure of the ITER cryostat is assumed to be 2 bar (absolute).

The main data are referred to the ITER Magnets [1].The principal arrangement of the TF and PF magnets are illustrated in Fig. 1 and Fig. 2 taken from [1].

Three different states for the TF and PF coils have been distinguished [1]:

- Normal operation

  While the TF coils are operated by the nominal constant current, the PF coils are ramped to drive and control the plasma. An oscillation of the PF coil current is assigned for sweeping the strike point across the divertor. Plasma disruptions are assumed to occur.

  During normal operation the coils must not quench.

- Abnormal or upset operation

  Occurring events can be coil quench, loss of coolant or loss of power, loss of cryostat vacuum, and earthquake. In any case the coils must be shut down safely and without damage.

- Fault conditions

  Among these are events like failure of the protection system (control failure), electrical short circuit, electrical open circuit (e.g. lead break), and mechanical failure.

  There is a strong demand to restrict the damage to the coil within its case and to confine possible radioactivity release within the cryostat.

For the superconducting magnets mechanical loads arising from coupling processes between the coils have dominating influence on the operating conditions. In the case of failures like shorts and arcs the occurring asymmetric current and load distribution will be further enhanced by electromagnetic coupling.

Other design constraints result from cryogenic temperatures, the heat load, and the radiation induced degradation of materials. Finally, the requirements of remote maintenance have to be taken into account.

2.2.1 TF Coils

Design criteria, the design concept, and the analysis of the TF coils are described in [1]. The general features are listed in Table 2-1, taken from [1].

Table 2-1: General Features of the TF Magnets

Number of TF coils	16
Total stored energy (GJ)	42.3
Total current per coil (MA)	9.094
Magnet dimensions (including case):	
Horizontal clear bore (m)	7.10
Vertical clear bore (m)	14.76
Clear bore dia. for CS (m)	4.26
Outer radial extent (m)	11.1
Height (m)	18.9
Field on axis (at 6.0 m) (T)	4.85
Maximum field at the windings (T)	11.2
Winding pack description:	
Pack dimensions (m x m)	0.306 x 0.846
Mean pack current density (A/mm^2)	35.1
Number of turns	240
Conductor current (kA)	37.9
Mass of the windings (t)	62
Mass of the case (t)	380

For the time being there are different options for the ITER superconductors. However, all of them have the following basic features: cable of composite strands, internal flow cooling by helium of supercritical pressure and a steel tube jaket. The principal configuration of one conductor of a cable-in-conduit type and one of monolithic type are illustrated in Fig. 3. In both cases the ternary Nb_3Sn superconductor is surrounded by a chromium plated copper stabilizer. The maximum hot spot temperature is assumed at 150 K for abnormal or upset operation.

In the conceptual design of ITER there are different designs of winding packs. On principle two types can be distinguished: the one pack design and a design of two symmetric halves.

Corresponding to the two types of winding packs there are again two types of coil cases.

Since the coils are cooled down and charged up for long periods the main components of the loadings, the in-plane loadings, remain constant. However, the pulsed operation of the machine leads to cycling out-of-plane loads. Therefore the total normal operating loads are a mixing of static and cyclic stress conditions.

Other loadings on structures are caused by gravity, differential thermal expansions, preloading, disruptions, quench effects and fault loading. Fault induced loads may be more severe, however, they should be less frequent.

The inner vertical legs of the coils are formed into a rigid central vault structure. Hence, the inward force on each leg is reacted by a toroidal compression within the vault. The forces produced by the poloidal field and acting normal to the TF coil plane vary around its perimeter. They result in zero net force but in an overturning moment about the coil symmetry axis. The central vault and the outer intercoil structure have to cope with these forces and moments.

2.2.2 PF Coils

Design criteria, the conceptual design, and various analyses are described in the ITER Documentation Series [1 and 2]. There are three separate sets of PF coils:

- The central solenoid with four up-down pairs (labelled PF 1 to PF 4) of superconducting coils. Besides the main function acting as transformer coils the solenoid also contributes to the plasma equilibrium. The solenoid is characterized by limited space and large compressive forces, hence, limiting the inductive drive of the plasma current. The maximum field close to the winding is 13.5 T at initial energization.

- The main superconducting coils outside the TF coils comprising three up-down pairs (labelled PF 5, PF 6 and PF 7). These outer PF coils serve for generating the plasma equilibrium fields and part of the inductive flux for the plasma. They have a position control function on a slow timescale of a few seconds. The coils are cooled by forced flow helium. The maximum conductor current is 30 - 40 kA. The maximum fields close to the windings are in the 5 to 8 T range, with a maximum rate of change of about 2.5 T/s.
- A pair of water-cooled normal conducting active control coils within the vacuum vessel (not shown in fig. 1). They stabilize the vertical position of the plasma and control fast vertical displacements. The single turn copper coils have a ceramic insulation to withstand high radiation dose.

The PF system shall provide plasma configurations and different plasma operating scenarios both for the Physics Phase and the Technology Phase of ITER. The nominal plasma current is 22 MA. In the Physics Phase, besides the baseline ignition mode with a burn time of 400 s, different extended operation modes are foreseen with plasma currents of 25 and 28 MA and burn times from 35 s to more than 400 s. The Technology Phase operation needs lower plasma currents, however, longer burn times up to quasi steady state operation are planned.

As mentioned above, from the safety point of view three different operation states have been distinguished. According to these three operation categories the design of the PF coils has to take into account the following loads [3]:

1. For normal operation
   - Magnetic hoop loads
   - Magnetic out-of-plane loads
   - Gravity forces
   - Thermal stresses during cool-down and warm-up
   - Preload stress to maintain contact between winding pack and support structure
   - Imposed displacement/rotation to the PF5 coil from support system attached to the TF coils
   - Ripple loading due to the PF component from the TF coils
   - A change in magnetic hoop load and magnetic out-of-plane load during a disruption.

2. For abnormal operation

   - Quench stress resulting from the heated helium, and from differential thermal stresses in the winding
   - Extra ripple loading from the poloidal component of the TF coils fields due to non-simultaneous discharge of the two PF coil circuits
   - Earthquake loads.

3. For faulted operation

   - Exceptional hoop or vertical forces due to failure of the power supply control system
   - Exceptional hoop or vertical forces due to a coil short circuit
   - High ripple loading due to a poloidal field from the TF coils when one of these is in a faulted condition.

Like the TF coils, the PF coils need cooling facilities to guarantee the operating temperature conditions.

2.2.3 Impacts on the Coils

As mentioned above the magnets are subjected to different operational loads to be analyzed during the design process. Among these are the pulse loads produced by the PF coils. Time variable magnetic fields induce eddy currents in the structures with the consequence of ohmic heating and mechanical loads.

Whilst the ohmic heating and other thermal loads yield the inputs to the specification of the cryogenic system, the mechanical loads have to be accomodated by a proper design of the structures.

An important impact on the design of the magnets and their supporting structures will result from plasma disruptions. Plasma disruptions are considered to be a normal operation status for the magnets. Hence, during a severe plasma disruption stable operation is required. For the magnets only the electromagnetic effects of a disruption are of relevance. The consequences of these effects are

- sudden field/current changes in the TF and especially PF coils with high induced coil voltages and alternating current (AC) losses. The AC losses should be removed by the coolant in due time such that the critical temperature for the superconductor are not reached.

- eddy currents in the structures near the plasma. These induced currents interact with the magnetic fields and produce electromagnetic loads. The induced currents and loads predominantly influence the in-vessel components and the vacuum vessel. The coil casings and support structures are subjected to only minor loads, which do not contribute to the overall load determination.

The superconducting cable is designed for a time scale of the plasma current decay in the order of 20 ms. This may yield field changes of 40 T/s in the peak field region of the TF coils in the vault. Disruption induced losses include hysteresis losses in the superconductor, coupling losses in the cable, eddy current loss in the conduit due to the transverse and parallel field components. Assuming a coupling time constant of 10 ms the local AC losses due to plasma disruptions are calculated with 93 mJ/cm^3 in the cable for the TF coils, 160 mJ/cm^3 for PF1 to PF4, and 5 mJ/cm^3 for the PF coils 5 to 7 [1].

An effect resulting from plasma disruptions may be a quench of the PF transformer coil since the high dB/dt values could exceed the capability of the cooling.Also a quench of a TF coil following a plasma disruption mainly due to conductor slip has been judged possible. A quench could be the initiating event for an uncontrolled heat-up of the concerning coil. This accident is considered in chapter 4.1.

The structural analysis of the TF coils both under normal and different fault conditions as performed during the conceptual design phase of ITER are illustrated in [1]. It shows the rather complex interrelation between the various electromagnetic loads and the mechanical behaviour of the coil system and its structure. Further analyses for the case of a short circuit and an open circuit seem to be necessary in order to find a design solution with a minimum slip of the inner legs.

With regard to the PF coils especially the central solenoid needs a very exacting design. Precompression of the winding packs is necessary to prevent gaps between packs and support flanges due to outward vertical forces dependent on the current scenario.

Since pulsed operation of the PF system imposes cyclic loading on all magnet structures, fatigue in structural components is a critical issue. A failure of the sheath of a cable-in-conduit conductor can occur mainly in the weld zone when a growing crack penetrates the wall casing and causes a leak. The material data base for fatigue crack growth rate (FCGR) in the temperature region of 4 K and the detectability of small flaws is still limited. However, recent results show that the FCGR in the weldings is lower compared to that of the base metal and further that the fatigue life of material is sufficient (10^6 load cycles) at cryogenic temperatures [4].

A thermohydraulic analysis has been performed [1] to determine the helium mass flow necessary to remove the heat loads with restricted temperature increase and pressure drop. The second aim of this analysis is to assess the location of the minimum temperature margin along the pancake length.

There is a relatively large nuclear heat input on the plasma facing side of the straight legs of the TF coils. Hence the minimum temperature margin is located in the first turn of the winding. The temperature distribution is mostly governed by nuclear heating, heat conduction and radiation to the environment, and frictional losses in the coolant. The contribution by the AC loss transient heat flux is of minor importance.

Another constraint influencing the magnet design is the nuclear radiation. To minimize the heat production within the coils, and to keep the radiation damages especially in the insulation materials within allowable limits shielding against nuclear radiation is necessary. The thickness of the shielding structures, e.g. the shielding blanket, has to guarantee that the specified dose limitation for the superconducting coils are not exceeded up to the end of NET operation time.

The radiation limits for the TF coils are due to the copper stabilizer, the epoxy insulation and the cooling. The copper stabilizers are subjected to a radiation induced increase in resistance. Generally the radiation damage to the insulation by a degradation in the structural and electric properties is the most restrictive parameter.

For the radiation exposure of the ITER TF coils the levels listed in Table 2-2 were assumed under the condition that a careful design and suitable materials are applied [1].

Concerning the neutron activation of magnet materials it is far less than that of plasma facing components and limited due to the necessary shielding against heat deposition and radiation damage of conductors and insulators. An exemplary activation assessment for NET conditions (neutron wall loading = 1 MW/m^2 after 1 yr of exposure) indicates that the near-term induced activity of magnet materials requires remote handling. Longterm activity is low allowing hands-on recycling of the magnet materials [5].

Table 2-2: Levels of Radiation Damage to be Tolerated During the Operational Life of the Magnet Systems

Insulator dose (Gy)	2×10^7 (average) 5×10^7 (peak, i.e. average over one conductor width)
Copper damage (dpa)	5×10^{-4}
Neutron fluence (n/m^2) (E > 0.1 MeV)	1×10^{23}

Under accident conditions the induced radioactivity may be of relevance in the case of arcing where melting and evaporation of material occur. This would lead to the contamination of the next barrier.

Besides the nuclear radiation the non-ionizing radiation of the electric, magnetic and electromagnetic fields resulting from the magnets, their power supply, and RF heating facilities has its impact on the plant design.

Protective measures will be necessary for the station staff and also for different electronic equipment. The potential hazard to the public seems to be of minor importance due to the performed protection of the workers which is mandatory in any case. Dose limits, both for the workers and the public, have to be observed.

2.2.4 Cryogenic System

The cryogenic system has to provide cooling for the superconducting coils, and for various other subsystems of the plant, e.g. the current leads, the cryopumps, the fuel processing and RF heating systems. Concerning the magnet system the total cooling weight amounts to 12000 tons. For normal operation the average heat loads of the magnet system are in the order of 100 kW.

The coils are cooled by forced flow supercritical helium with an inlet temperature of 4.5 K, an outlet temperature of about 6 K, and an inlet pressure of 5 - 10 bar. The total mass flow rate is 10 - 15 kg/s and the pressure drop amounts to 1 - 4 bar [1].

For off-normal operation, i.e. in the case of a coil quench, the helium inside the magnet should be drained to a recovery tank without delay in order to limit the pressure rise in the magnet. The emergency storage of helium seems to need further investigations.

2.2.5 Power Supply and Control Systems

The power supply systems consist of three different groups:

1. The power supply of the TF coils

   The main components are:

   - Transformer from high voltage supply
   - Converter
   - Discharge circuit breakers
   - Discharge resistors

2. The power supply of the PF coils

   The main components for each coil or each coil pair are:

   - Transformers from high voltage supply
   - Converters, switches and resistors to extract energy from coil system and to switch converter configuration
   - Discharge circuit breakers
   - Discharge resistor

3. The power supply of the active control coils

   The main components are:

   - Transformer from high voltage supply
   - Fast response amplifier.

The magnet power supply systems have two main functions: to provide the power to generate the fields for the magnetic confinement and control of the plasma, and to protect the coils by a safe energy discharge system. The protection circuits of the TF and PF magnets are planned to provide a fast discharge in the case of a coil quench with a time constant of 10 s, and a slow discharge in pre-emergency situations with a discharge time of 0.5 h.

The stored energy in the TF coils is 42.3 GJ. In the PF coils the variable stored energy and the high coupling between coils yield complex discharge conditions. In the different coils the maximum values of the stored energy vary in the range from 1.0 to 5.0 GJ [6].

Due to the hazard potential of the stored electromagnetic energy, because of the high investment costs, and due to the fact that the superconducting coils are considered to be semi-permanent components the reliable protection of the magnet system is an essential general demand.

For the quench protection system the following parameters are defined [1]: the maximum hot-spot temperature must not exceed 150 K, the maximum coil voltage between terminals or between a terminal and ground is limited to 20 kV, and the maximum conductor current is fixed at 40 kA.

Since the quench protection circuit is the most critical part of the TF power supply system different designs are under discussion. All schemes are based on a series-alternating connection of coils and circuit breakers, however, the kind of dump resistor connection is different. For the time being a preference is given to a circuit scheme as illustrated in Fig. 4. Here the mid points of the magnet dump resistors (R1-R32) are connected by additional resistors (R33-R48) to the common bus bar.

The power supply of the superconducting PF coils is even more complex than for the TF coils. This is true because either each coil or each up-down coil pair requires an individual supply. Furthermore, the power transfer rate can be quite large during a pulse scenario. A reference burn cycle during pulsed operation is about 400 s. The necessary power depends furthermore on the power supply layout and on the need for sweeping of the separatrix in the divertors.

The power supply of the TF coils is about 50 MW. For the PF coils it is determined by the interaction with the plasma including both delivering and absorbing power. The maximum net input power from the supply system is below 400 MW. The negative net power amounts to about 450 MW. Here energy is feeded to the grid.

The design conditions and criteria for the power supply and protection systems are described in detail in [1, 2]. However, there are some open questions in the overall specification and concerning special components.

Concerning faults it seems that control malfunction is the most severe fault of the PF coil power supply. Switching malfunction is considered to be the most severe fault for the TF coil power supply. For both coil systems the consequences in terms of electric, thermal and mechanical impacts will require more investigations when the design of the power supply and protection systems is known in more detail.

2.2.6 Auxiliaries and Diagnostics

Auxiliaries include especially coolant subsystems of the magnet system others than liquid helium, and corresponding coil services. They are not considered here.

Some attention, however, is directed to the diagnostics.

Both TF and PF coils need subsystems for maintaining the control & drive functions and for protection of the magnet system, as already mentioned in chapter 2.2.5.

The different diagnostic subsystems of the magnet system perform two primary functions:

- they provide control systems which guarantee the orderly and safe startup, operation and shutdown of the magnet system, and
- they provide instruments to acquire the experimental and operational data for the different test programs.

According to the safety standards, e.g. as they are valid in the light water reactor technology in Germany, a complete separation of the control system for normal and transient operation and for the magnet protection should be achieved. That means, two independent systems where the safety system has priority over the operation control system. The safety system has to guarantee that the magnet systems during failures and disturbances but also in the case of accidents could be brought back into a safe state.

The main diagnostic devices are necessary for measuring coil parameters like temperature, coolant mass flow, coolant pressure, current, voltage, strains, magnetic field and flux changes, possibly acoustic emission, and events like quench and short circuits.

The main purpose of the protection subsystem is to minimize the consequences of any kind of failures originating from the magnet system. This includes consequences, both for the magnet and the whole plant. Hence the following parameters are to be limited:

- Temperature rise in the coils
- Mechanical overloads on the coils and structures

- Overpressure in the cryostat
- Propagation of accidents, such as fire, mechanical damage, etc.
- Quantity of radioactive releases.

Since the instrumentation for the magnet system is not yet specified a more general information is given in the following.

During installation of the instrumentation, attention has to be paid to the electrical insulation between winding and instrumentation. Experiences from the LCT project lead to the recommendation to avoid, if possible, sensors within the windings. Feedthrough techniques are needed for routing the instrumentation wires out of the coil to avoid leaks from helium to tank vacuum.

Coil instrumentation includes sensors, cabling from the sensors to the control room, and signal conditioning units. Some of these units are equipped with local displays, some with output to the data acquisition system for display and storage, and some with output to the coil protection system to provide automatic dumping action.

Concerning reliability and availability of the magnet system it is stressed again that especially the instrumentation devices yield a high and sensitive contribution. This is underlined also by a study on the reliability and availability of protection, instrumentation and control installations for the TF and the PF coils [7]. There is a lot of information on types and numbers of appropriate instrumentation including recommendations on redundant arrangements of different devices.

A direct link between the plasma conditions and various sub-systems is provided by the pulse termination network. It receives signals from the plasma position, the current control, and the plasma fault protection systems. The latter system has to detect disruptions and to provide backup protection for feedback of plasma current and density.

The need for a reliable and efficient plasma control will be one of the most important issues especially with regard to reduce the number of plasma disruptions. These can result from unsuitable plasma control. Even when a thermal disruption has occurred, it is necessary to control the plasma position and to reduce the current decay rate.

3. Possible Magnet Failure Events

3.1 Magnet Failure

As already mentioned above, the safe and reliable operation of the superconducting magnets is considered to be a considerable challenge for the design of a fusion machine. Therefore, it is important to consider magnet failures occurred in the past, and to use this experience in the design and system analysis.

As an interesting example the failure in a coil of TORE SUPRA as reported in [8] should be mentioned. Due to the unexplained presence of a metal particle a short circuit between two pancakes occured. Previous and present engineering problems in magnet technology have been collected by D.B. Montgomery [9], taking into account other pertinent reports. The conclusions of these investigations - literally cited - are:

"(1) Failures are more commonly associated with insulation than with the conductors. (2) Failures are almost as likely to occur in the leads as they are in the coils, probably because these details recieve minimal attention. (3) The causes of failure in the data base were classified as associated with specific design errors or oversights (unanticipated conditions) in two thirds of the entries."

A very recent review of magnet operating experience has been performed by L.C. Cadwallader [10]. The summary of failure events is broken down by initiating event categories. The document is supplemented by particular items of order-of-magnitude of failure rates. These failure rates were derived mainly from industrial experience with similar components.

In the literature various safety related considerations on s/c magnets are discussed as for example referred to in [11 - 17]. The most recent report on ITER safety [18] will be adressed later on.

The previous assessments indicate that the fundamental questions for the safety of s/c magnets are the following:

Does the relatively large amount of stored energies within the s/c magnets jeopardize the safe operation of the magnet system in the case of an uncontrolled release? Are there initiators and subsequently sequences of events which might lead to deformations or destructions of a magnet and in consequence to destructions of structures confining radioactivity?

The high amounts of stored energy are due to the required high magnetic field and its large volume. It leads to high inductances and operating currents. Disturbances in the magnets as a quench, a short or an arc may lead to heat production in the coil windings or to strong nonsymmetrical electromagnetic forces or to pressure rise in helium-filled conductors/containers or to a combination thereof. After detection of the disturbance the energy usually is distracted from the magnets and dumped in an external resistor. Safety relevant events are therefore those where this energy transfer is hindered or even made impossible as conceivable for various shorts and arcs arrangements within or outside the coils but within the cryostat, or outside the cryostat in the power supply/dump circuits.

Experimental investigations of the relevance of a number of different fault initiations and consequences in the TESPE experiments at KfK [19 - 22] and the Large Coil Task at Oak Ridge [23] showed the tolerance of the magnet systems with respect to loss of flow for more than ten minutes, or to the malfunction of the current breakers or quench detectors for a few seconds. The faults of most concern are shorts, arcing inside the coils, arcing across the leads and arcing in the series current connection between the coils or their power supply. It is possible to operate the magnet set with a shorted coil and not be aware of the fault until the system current is changed. Conversely, the presence of an arc or short may require that the operator discharge the coil at a slower rate than usual or even to suspend the discharge. Hence, it should be investigated if an automatic magnet control system will be able to diagnose failures in the magnet system in some detail before dissipating the stored energy.

It is stressed again that the most severe problem seems to be arcing since the significant mechanism for an undesired transfer of the stored energy with destructive consequences mainly occur by arcing. Hence, the main objective is to avoid or reduce initiating events leading to arcing and to mitigate the consequences.

A direct result of this is to take special care in the design and manufacturing of the s/c magnets. An extremely high standard of quality assurance is a necessary basis for a high degree of operational safety, availability and reliability of the magnet system as a whole.

Based on investigations for NET a classification into reference accident sequences was performed [24]. This classification gives a coarse envelope to cover the main events and the most important failure modes. They may be grouped according to a functional analysis into direct failures and induced failures.

If a failure of a system, subsystem or component can directly cause a loss of a process function of the system it is called direct failure. If a failure of a system, subsystem or component can cause a failure of another system, and thus these failures can indirectly cause a loss of function, it is called induced failure.

3.2 Definition of Reference Accident Sequences (RAS)

In the category of direct failures the following magnet reference accident sequences are considered:

RAS-1a: Uncontrolled growing of a normal conducting zone

This accident means a normal conducting zone with no recovery. The normal conducting zone may be generated by a local heat production or an abrupt movement of a winding part. The additional assumption is that the dumping system does not work, so that a so-called thermal failure propagation will occur. The main focus of this accident is whether, and if so, what kind of structural failure has to be expected for the coils. If during the accident a loss of coolant sequence is entered the consequences should be covered under that accident sequence. It is assumed that the sequences can be superimposed.

RAS-1b: Low Ohm shorts and arcs on a magnet

This sequence again has the main focus on structural failure. The reasons for such a failure may stem from currents in the magnet system different from those assumed for the design; either by a low Ohm short or by an arc or an erroneous status of the current switches for the PF coils.

RAS-1c: Loss of insulation vacuum (LIVA)

The loss of the cryostat vacuum boundary, due to causes external to the magnet system, is assumed. The initiating event can be a breach of the cryostat boundary or a LOCA in a cooling pipe, outside the vacuum vessel, followed by the rupture of the containment pipe, which is assumed to surround all the pipes within the cryostat.

The main focus of this sequence is to evaluate the consequences on the overall system due to the global heat-up ramp for the coil systems. This, in fact, could make the pressure transient in the cryostat worse than that being studied in RAS-1d.

RAS-1d: Loss of cooling for the coils (LOCA)

A LOCA may arise following a break of a manifold or a pipe due to mechanical reasons or following to a break of a coil due to extended arcing. The helium lost in the cryostat is heated up by the stored magnetic energy through the structural masses or by the arc. The main focus of this accident is to study the pressure transient in the cryostat.

Another sequence in the category of direct failures is the spontaneous rupture of a coil due to crack growth. In [42] it was assumed that coil case and winding pack fail simultaneously, in [43] only a failure of the coil case or parts of it is assumed. Depending on the design of the coil case this sequence has to be reconsidered.

Concerning the induced failures the following magnet reference accident sequences should be taken into account. Two kinds of induced failures are considered: failures the origin of which lies in others than the magnet systems, and failures correlated with plant external events.

RAS-1e: Fire

A fire may occur within the cryostat, outside of the cryostat or in the vacuum vessel. In the first case a failure of the cryostat, burnable materials like cable insulation and an igniting temperature, e.g. an arc, are required. The amount of stored energy and the number of necessary conditions show that this event is unlikely. In the second case current and coolant lines as well as dump resistors may loose their function for the magnet system. More detailed design is required to see how such events can proceed. The third case follows from a severe accident in the vacuum vessel, e.g. a graphite fire where local heat loads could occur at the magnets.

The main safety demand for the design of the magnet systems is a safe shut-down and maintaining the magnet systems (and the plant) in a safe condition. Furthermore, it should be ensured, that the likelihood of any release of large amounts of energy or radioactive or toxic material remains within prescribed limits during and after any fault condition.

RAS-1f: Loss of off-site power

Loss of off-site power is an event which may result as a secondary effect from man-induced hazards like human intervention, or from natural-induced hazards like seismic events or lightning stroke. Initiating events should be considered to occur not only outside but also inside the plant.

In case of a loss of off-site power the main safety demands on the plasma and the magnets are first a safe shut-down of the plasma burning process, and second a safe discharge of the PF magnets.

RAS-1g: Earthquake

To minimize the earthquake loads on the coils the support structures of the magnet system have to be designed properly. The general aim of protection of the magnet systems against earthquakes is to provide means to safely shutdown the magnets and to maintain them in a safe condition.

For the magnet systems the following items are of special concern:

- The discharge system,
- the design of the legs of the TF coils to avoid interactions between the magnets and the vacuum vessel in small gaps,
- the design of current leads and coolant lines.

The seismic hazard depends strongly on the geographical location. For example in Europe the earthquake map shows high and medium seismic activities in the south and low seismic activities in the north. A strong site dependence also exists for the response spectrum of the ground.

RAS-1h: Drop of a heavy load

A typical heavy load that could drop on the magnet system is a blanket segment while it is exchanged. This can happen only during maintenance when the plant is shut down. The component that will be affected most by such an event is the cryostat. Other sensitive components are the coolant and current lines below the magnets. For a more detailed design it has to be checked which load could cause such an event. However, no release of radioactivity has to be anticipated.

Design measures as redundant cables on cranes or interlocks for the handling units should be used to adequately reduce the failure probability.

RAS-1i: Local external heat input to a coil

This accident has its focus on the upper connection box, where the supply lines for the blanket segments run nearby the TF coils. If it is assumed that a loss of coolant accident in the blanket cooling system occurs in this box, it will be heated up to coolant temperature. The question is whether the structure can withstand the hydrostatic load of the coolant or whether it fails. Another question is whether the magnet insulation will fail and the vacuum is lost (RAS-1c). In both cases additional heat loads are exerted on the coils.

The heatup ramp for the coils as a function of the events indicated has to be determined and compared with ramps due to other events with similar consequences, like the loss of insulation vacuum (LIVA)

RAS-1j: Magnet field induced missiles

An accident may also be caused by loose parts, such as tools, accelerated by the magnetic field. In the worst case it might be assumed that these parts which act as a missile breach the cryostat. The loss of vacuum would then lead to a magnet quench with the consequence of a plasma disruption.

To avoid such missiles the presence of loose parts, i. e. tools or components, in the cryostat has to be excluded by engineering and administrative measures during the design, construction and maintenance.

For the induced failures RAS-1e, RAS-1f and -1i it is assumed that they don't initiate new accident sequences. They rather will amplify the probability of one of the sequences mentioned before. RAS-1g and RAS-1h are assumed to be covered by design.

This study will focus on the assessment of the direct failures listed above and their consequences.

The actual state of the ITER magnet safety analysis as a result of the conceptual design phase is reported in [18]. It seems worthwhile to cite literally what ITER safety people have summarized on the magnets:

> "The magnet system does not contain significant radioactivity inventories but the large energy inventory is a potential accident initiator. In theory without good design, magnets could release energy in such a way to damage the vacuum chamber, coolant lines, or fail confinement barriers. Safety assessments of the ITER magnet system suggest that this is not possible. The key issue for detailed engineering and analysis is to insure that movement of inboard coil legs is not possible in transients with unbalanced currents and forces."

Taking into account this statement and the considerations mentioned above the main problems arise from those events in an accident sequence having the potential to the release of radioactivity into the environment.

Hence, magnet safety should focus on the analysis of reference accident sequences including events which have a potential to propagate from the magnet system to adjacent components. As a basic design requirement of the NET/ITER magnet system it was assumed by the ITER magnet designers that any fault and related damage should be confined within the magnet system without jeopardizing adjacent components. This means that the magnet system itself acts as the first barrier. The assessment of the extent to which this requirement can be fulfilled should be a major objective. Otherwise, the integrity of further barriers against the release of radioactivity has to be addressed. A conceivable failure propagation process is illustrated schematically in Fig. 5. Radioactivity release to the environment is only possible if the last confinement barrier would fail.

In this sense, especially the following events are considered to have a potential of failure propagation. Essentially, these events are considered to be critical ones also by other safety experts [25].

(1) Uncontrolled growing of a normal conducting zone
    with the main question of the maximum coil temperature reached

(2) Influence of shorts and arcs on the coil behaviour with the two areas:
    - Electric arc outside a coil
      with the main question of the affected environment

- Electric arc inside a coil
  with the response of the coil to the mechanical and thermal loads

(3) Coil deformation or displacement
    due to exceptional electro-mangnetic or thermal loads

(4) Volume change of cryogenic helium
    due to a loss of coolant accident with helium expulsion into the cryostat, or initiated by a loss of insulation vacuum.

In the following chapter these events are dealed with in a more detailed manner. The influence of shorts and arcs on the coil behaviour is illustrated in this report with regard to the toroidal field coils. The main objective is to demonstrate whether an accidental sequence of events may be stopped in an early phase. This would mean that severe magnet failures will not propagate to an extent that results in jeopardizing adjacent components and finally the environment of a fusion plant.

With regard to the present knowledge on magnet safety and the status of the development of the design the extent of the safety analysis is limited. Therefore, this report is considered to be of preliminary character with the necessity of a stepwise iteration of the safety analysis in parallel with the evolving design.

4. Assessment of Critical Events

4.1 Uncontrolled Growing of a Normal Conducting Zone

A preliminary investigation on the consequences of an uncontrolled growing normal conducting zone with the code system MAGS [26] indicates that an unclasp of a coil is not to be expected [27]. The prerequisite for such a failure would be a local heat up of a coil cross section so that mechanical failure due to the combined mechanical and thermal load would occur. The temperature distribution found so far shows no localized heat production in the coil. Due to the winding technique and the flow of the hot helium there are alternating hotter and colder channels. The hot zones primarily propagate in circumferential direction, as can be seen in Fig. 6 showing the coolant temperatures of a TF pancake 7.5 seconds after a spurious local quench.

The average quench velocity is difficult to estimate because it is strongly varying. Main parameters are the intensity of the magnet field and the current density. If the average is taken over several seconds the quench velocity in a pancake is about 50 m/s.

Temperatures in the cable space are growing with 70 K/s and 100 K/s for operational current and 150 % current, respectively. The cable jacket temperatures follow with some delay. In a rough estimate the jacket temperature is found to be roughly 60 % of the cable temperature for the transients considered here. The insulation temperatures lack even more. They are in the order of 20 % to 30 % of the cable temperature.

The pressure in the cable can easily grow beyond the design pressure of the cable (greater 200 bar).

The behavior of the inlet manifold seems to be very important. It promotes propagation of a normal conducting zone because hot helium from one pancake can be pressed into all other pancakes (see Fig. 7 and 8). Furthermore, the plenum has to withstand the same extreme pressures as the coolant channel if no depressurization takes place.

After a transient time in the order of 10 to 20 seconds also the outlet plenum is exposed to high thermal and mechanical load as previously the inlet plenum. Then a failure of the bus bar and arcs on them seem to be likely. More detailed analysis is necessary to evaluate the consequences.

4.2 Influence of Shorts and Arcs on the Behaviour of the Toroidal Field Coils

Under normal operation - for both the phase of constant current and the phases of charge or discharge - the TF coil circuit exhibits symmetrical current distribution. Disturbances of symmetry by inductive coupling with the pulsed poloidal coils are not to be expected. Slight differences of the current in the TF circuits of NET may be generated by different delays during the opening of discharge switches. These differences do not mean a major disturbance of symmetry. However, in case of fault operation the current distribution can become strongly asymmetric. After an introductory description of the behavior of the TF coils under normal conditions, the behaviour of the TF current in case of a short-circuit and of arcing is discussed. Here a distinction is made between the two-circuit system of NET and the one-circuit system of ITER. The work done at KFK/ITP with respect to shorts and arcs in magnet safety is summarized in [28].

The question of 'missile generation' has been investigated but it is not discussed here in detail. Recent analyses [29] were rendered possible after numerous experiments with arcs in magnet systems and appropriate evaluation. The present state of discussion can be briefly summarized as follows: In case the missile generation is not excluded by design, the kinetic energy due to the missile acceleration in the magnetic field will only be in the same order of magnitude as the kinetic energy due to a free fall of the missile. Measures could then be taken by design to limit the damage of the 'missile' on the magnet system. Further analyses, however, will have to be performed. Moreover, a different view should be taken on the long arc established after the missile has gone. Surrounding components may be hit by that arc burning in the current path of the magnet system.

4.2.1 Coil Current for Normal Operation

Discharge of the magnet system is started by opening of the switches bridging the discharge resistances. In order to avoid high voltages, a partial resistance is allocated to each coil. For the calculational model the partial resistances on the one hand and the self and mutual inductances on the other hand may be considered as a whole. With the assumption of approximately simultaneous opening of all switches the current characteristics is simplified. The discharge time constant T is given by the ratio of the total inductance of the TF circuit and the discharge resistance R. The current variation in time shows the well-known exponential shape. For equal discharge resistances the transient currents in the

ITER and NET circuits, are the same, too. In case of non-simultaneous opening of the switches differences occur between the two systems. While there is only a change of discharge time constant in case of ITER, different currents will flow in the two NET TF circuits.

For NET additional peculiarities of current distribution may occur due to the division into two circuits. If it is possible to switch both circuits indepently of each other, one circuit may be discharged while the other continues to carry the full operating current. The two circuits show conductive de-coupling while they are strongly coupled by magnetic induction. Current variations in the second circuit are generated when the current in the first circuit is changed. While the current in the circuit under discharge decreases with the given time constant, the current in the second circuit increases up to a maximum value which is described by

$$I_{1,max} = I_0 (1 + M/L_1) = I_0 (1 + k_{circuit})$$

with L_1 = 17.3 H the inductance of one circuit, M = 11.5 H the mutual inductance of the circuits and $k_{circuit}$ the coupling coefficient of the two circuits.

For NET the complete discharge of the first TF circuit leads to an increase of the current in the second circuit up to 166 %, i.e. for an operating current of 37.9 kA an increase up to 63.1 kA is conceivable if the coil remains superconducting.

4.2.2 Current Distribution in the TF Coil Circuit in Case of Short

The analyses presented below were done with the simplifying conservative assumption that the heat generated by a short or arc does not induce a quench of the superconducting coils.

A short-circuit bridging e.g. a coil or a pancake, for instance, considerably disturbs the symmetric current distribution during charging or discharging of the system. The induced current in the shorted circuit can grow significantly in systems like ITER or NET which have a large coupling coefficient between coils. As an example, the case of a shorted coil exposed to a fast discharge of the system is calculated. The solution allows also the calculation of a shorted pancake, a shorted winding or any other shorted partial inductance.

For the mechanical design of the coil case and the intercoil structure the maximum of current increase in the shorted coil is of importance. Therefore the present consideration ignores quench due to overriding the critical current of a specific superconductor design. Here both the maximum radial force and the maximum lateral force are found acting on the coil and its case. The maximum possible current in the shorted coil is calculated for infinite time and for the assumption of an ideal short, i.e. $R_{sh} = 0$. The discharge of the ITER TF system with one shorted coil enhances the current in this coil by a factor of $(1 + k_{coil}) = 2.58$. For a complete discharge of the NET system, i.e. simultaneous discharge of both circuits, the current in the shorted coil experiences the same increase. Beginning with 37.9 kA the maximum reaches 97.8 kA, if the coil remains superconducting. This value should be taken as a basis for the mechanical design.

At the beginning of discharge the short resistance R_{sh} influences only slightly the increase of coil current while it becomes decisive for the rest of the current characteristics. Figure 9 clearly shows that short resistances up to 1 mΩ still allow the induced current to reach nearly the maximum value of 97.8 kA mentioned before. After a broad maximum at 40 s the current starts to decrease slowly. With increasing short resistance the energy deposition in the short grows. The decay of the induced current in the R_{sh} is accelerated. The pronounced maximum is reached at shorter time. For the rather large resistance $R_{sh} = 100$ mΩ a maximum current of 52 kA is reached after only 12 s, followed by a fast decrease of the current in the shorted circuit.

4.2.2.1 Peculiarities of the NET Two-Circuit System

For the two-circuit TF system of NET special behaviour results when for any reason only one single circuit is discharged instead of two. In spite of the short in the first circuit the discharge of the undisturbed second circuit leads to an equal current increase in the first circuit: The currents $i_1(t)$ and $i_{coil}(t)$ are the same. Under extreme condition ($R_{sh} = 0$) they can reach 63.1 kA. The short-circuit has no influence on the current distribution if only the undisturbed coil circuit is discharged. The current in the short is zero. This behaviour can be explained by absolute symmetry and same coupling between the coils.

However, if the first circuit with the shorted coil is discharged, the current decrease in the remaining 7 coil circuit leads to a current enhancement in the second circuit by 58 % up to nearly 60 kA. The current in the shorted coil $i_{coil}(t)$ is slightly decreased down to 34 kA. This behaviour is explained by two counteracting tendencies: A decrease of $i_1(t)$ in the first circuit is followed by an increase of $i_{coil}(t)$, while the simultaneous increase of current in the second circuit reduces $i_{coil}(t)$.

4.2.3 Determination of the Arc Voltages for NET/ITER

Transfer of the experimental results obtained at TESPE to NET and ITER is done in two ways, first the laws of similarity are applied and second a linear approximation is performed. Voltages are found between 180 V and 300 V for an assumed arc of 20 mm length in a spatially restricted environment, e.g. inside a coil. Taking into account the additional influences of a magnetic field and gas pressure the voltage range to be applied for analyses is enlarged. For a 20 mm arc values between 180 V and 400 V can be used with sufficient confidence for calculations of current and force distribution.

In addition, it can be shown that also the voltage of a free burning arc outside a coil will have a rather limited range. For calculations of current distributions in NET/ITER with a system current near 40 kA arc voltages between 150 V and 300 V may be used for a free burning arc of 20 mm length.

For the higher voltage levels the voltage is roughly proportional to the arc length.

4.2.4 Current Distribution in the TF Coil Circuit with an Arc across one Coil

An arc across the terminals of one coil may be ignited e.g. by an electrical breakdown or after burnout of a short-circuit during a system discharge. The voltage between windings, for the "one-in-hand" winding technique applied, during a fast discharge is not higher than 50 V and is not sufficient for an electrical breakdown. Here arcs might only occur through disconnection of shorts. Application of the "two-in-hand" winding technique for NET produces much higher voltages between neighbouring windings of 900 - 1000 V. This value may be high enough for a breakdown in case of local faults of the insulation.

For the following discussions it is assumed that the arc is ignited across a complete coil immediately after beginning of discharge, further that the arc voltage reaches its final value at once and is constant for the burning period.

Figure 10 shows the current characteristics for a fast discharge of ITER and the total NET TF coil system, resp., when an arc burns across one coil. The calculation is performed for voltages between 150 V and 400 V. The time dependence of the arc current is described by

$$i_{arc}(t) = I_{coil,0} + I_{sys,0} \cdot k_{coil} - I_{sys,0} \cdot (1 + k_{coil}) \cdot e^{-\frac{t}{T_{eff}}}$$

$$- \frac{V_{arc}}{R_{dump}} \cdot (1 + k_{coil})^2 \cdot (1 - e^{-\frac{t}{T_{eff}}}) - \frac{V_{arc}}{L_{coil}} \cdot t$$

with

$$T_{eff} = \frac{L_{sys} - \frac{M_{coil}^2}{L_{coil}}}{R_{dump}} \qquad \wedge \qquad k_{coil} = \frac{M_{coil}}{L_{coil}}$$

In contrast to the case of short-circuit coil current $i_{coil}(t)$ and arc current $i_{arc}(t)$ decrease linearly beyond the maximum. For an arc voltage of 200 V the following data are calculated: The arc current reaches 91 kA, which is close to the maximum value for an ideal short-circuit. The following decrease of $i_{coil}(t)$ and $i_{arc}(t)$ has the velocity of 143 A/s. The total arc burning period is 684 s. Within this period roughly 6.5 GJ of the stored energy are converted in the arc. Increasing voltage leads to a reduction of burn time but also to burning at higher power level. It can be shown, however, that the converted energy is approximately independent of the arc voltage. Remaining uncertainties of the arc voltage are, therefore, not significant.

4.2.4.1 NET Peculiarities

Regarding the current distribution in the TF coil circuits of NET with one arcing coil and the discharge of one circuit only, the obtained characteristics are similar to the case of a short. During discharge of the undisturbed circuit a short-circuit over any inductance cannot burn out and produce an arc because of the short current being zero (cf. 4.2.2.1). In case of discharge of the disturbed circuit with one shorted coil an induced current flows through the short or through the later arc. An increase of the coil current is not observed. Nevertheless, the arc current can reach a maximum of 34 kA. The arc energy again is approximately independent of the arc voltage and is calculated with 830 MJ.

4.2.5 Current Distribution in NET/ITER TF with an Arc in Series to the Current Path

Break of a current carrying conductor in an inductive system always leads to an electric breakdown. For sufficiently high energy stored and a sufficiently high current this electric gas discharge leads to the development of an arc where at least a part of the stored energy is converted to heat.

Melting or mechanical break of the superconductor inside a TF coil or of a current lead or of a current bus is inevitably followed by ignition of an arc. Without any action the complete TF circuit of ITER would be discharged by an arc (roughly 40 GJ). This case has the highest destructive potential for the TF system of ITER. The current reduction rate is determined by the ratio of arc voltage and the inductance of the circuit. For an arc voltage of e.g. 300 V the current is reduced by 5.2 A/s.

A mitigating measure is here the fast discharge of the total TF system. It reduces the convertable energy in the arc. The current characteristics then hardly differ from the regular fast discharge as the arc voltage is small compared to the discharge voltage. The convertable energy is approximately proportional to the arc voltage e.g. 106 MJ for 200 V and 212 MJ for 400 V.

Deviations from the discussed current characteristics result for the case of an arc burning inside the coil after break of the conductor because the local heat production will induce a quench. The corresponding increase of the ohmic resistance in the circuit absorbs part of the energy and this reduces the arc energy. Therefore a fast quench propagation and a quick increase of ohmic resistance is highly desirable.

4.2.5.1 NET Peculiarities

In case an arc in the current path would remain undiscovered in NET, only the disturbed circuit discharges while the current in the second circuit is enhanced. For constant arc voltage the current change would be linear in both circuits. For an arc burning with 300 V the current in the disturbed circuit is reduced by 31.2 A/s. Here the current change is determined by the ratio of arc voltage and the effective inductivity for one-circuit-discharge. The current in the second circuit increases by 20.6 A/s up to its maximum value of 63.1 kA. The energy converted in the arc amounts to 6.9 GJ and is independent of the arc voltage but depends on the effective inductivity and the related stored energy. For this discharge case the effective inductivity is calculated as 9.6 H, which corresponds to a stored energy of 6.9 GJ.

The properties of the chosen superconductor can also cause changes of the current characteristics. If the current in the undisturbed second circuit reaches its critical value the conductor quenches. The increasing ohmic resistance in the coil leads then to a discharge of the second circuit which in turn couples energy back to the first circuit where the arc current and the arc energy can increase. For this case it is desirable to design the superconductor to take the full induced current without quench. Otherwise the quench propagation should produce only low ohmic resistance which, however, would be in contradiction to the aforementioned (4.2.5) requirements.

The possibility to discharge the two circuits independently of each other can lead to a reduction of the arc energy in comparison with the case of common discharge (cf. e.g. 4.2.4.1 and 4.2.4; 4.2.5.1 and 4.2.5). However, also the contrary becomes true when in case of an arc in the current path the disturbed circuit is not discharged while the undisturbed is. This represents the case of highest destructive potential in the TF system because additional energy is coupled from the second circuit to the disturbed first circuit. Independent of the arc voltage the arc energy can reach 34.5 GJ, i.e. about 84 % of the total energy stored in the TF system. Therefore, especially this case has to be avoided by any means.

4.2.6 Examples of Possible Behaviour of an Arc in the TF System

Examples of possible behaviour of an arc and its consequences for the NET/ITER TF coil system are discussed in the following. A short-circuit inside a coil leading to ignition of an arc during discharge is a fault which rather frequently occurs, see also [9]. The latest report on such a fault is given for TORE SUPRA [8]. Break or melting of a current lead or of a current bus between coils followed by an arc in the current path cannot be strictly excluded. For instance, it is shown here that this case can be a final consequence of a first arc ignited after burn-out of a short. Finally, arcing after electrical flashover or breakdown at current carrying parts during a fast discharge is reported to have occurred during coil tests of the T-15 tokamak [30].

4.2.6.1 Development of an Arc Inside a Coil after Burn-Out of a Short

It is assumed that a metal chip is included e.g. in the turn-to-turn insulation during winding. The magnetic forces acting under operational conditions may cause the chip to pierce through the insulation producing a short-circuit. For two-in-hand wound coils this means a short between two halves of a double-pancake. Further it is assumed that this short is not detected during the constant current operation period of the TF system, but it becomes effective during a regular (fast) discharge caused by operational requirements. A current is induced in the shorted circuit. Reaching the melting point of the chip the current in the short may attain several 100 A corresponding to a considerable amount of coupled energy. Disconnection of the current path in the short-circuit by melting will lead to an interruption of current flow. However, the originally shorted inductance with the coupled-in energy then supplies as high voltages as necessary to ensure current flow by ignition of an arc. Strong coupling into the arcing circuit further enlarges that current. The burn time and the arc energy depend on the arc voltage and on the quench propagation. A short arc of only 1 mm length can burn up to 80 s with a mean voltage between 60 V and 100 V. The arc current can rise depending on the winding ratio of pancake and coil by at least a factor of 10, and a total energy up to 1 GJ may be converted to heat. Taking into account the high current and therefore a higher voltage of e.g. 200 V and, in addition, assuming fast quench propagation, then the burn time is reduced to a few seconds. Nevertheless, the steel casing of the conductor and the conductor itself will be heavily damaged by the arc acting like a plasma burner. The converted energy still is sufficiently high to melt and evaporate several centimeters of conductor. Complete local melting of the conductor leads to ignition of a new arc, this time in the current path, which represents the case with the highest destructive potential (cf. 4.2.5).

Attempts to avoid ignition of an arc after burn-out of a short by reduction of the system's discharge voltage were not successful. As shown by experiments there does not exist a discharge voltage limit below which arcs could be avoided [31].

4.2.6.2 Arc Following a Voltage Breakdown Outside a Coil

The discharge of the TF coils is connected with high voltages of e.g. 20 kV at the current terminals of a coil. The electrical insulation is given by organic insulator plus the isolation vacuum. The conceivable damage of the insulator and the possible loss of vacuum drastically reduce the electric strength. Local deterioration of the vacuum can e.g. occur near current leads due to leaking coolant supply terminals. Therefore, the high voltage can lead to an electric breakdown and finally to the ignition of arcs.

The arc can be ignited e.g. between two current leads of a coil. The free burning arc outside the coils has a rather low voltage ($V_{arc} < 300$ V), compared to the system discharge voltage, and initially behaves like a short-circuit, i.e. the coil current increases, and energy is coupled into the coil. Maximum energy convertable in the arc is here 6.7 GJ. A part of the energy will be transferred to the increasing ohmic resistance generated by quench propagation. Nevertheless, the energy of the electrode spots of the arc, heating directly the material, amounts to 300 MJ to 500 MJ. Therefore, complete melting of the leads and separation of the coil from the remaining circuit is conceivable.

It is also possible that an arc is ignited and burning free between a lead and neighbouring reactor components which are usually at ground potential. The arc moves on its electrodes and can also jump to sharp edges to be localized there. If highly sensible components like control leads or even tritium or other radioactivity containing pipes are located near the arc, then thermal damage or destruction cannot be excluded. Therefore complete electrical insulation of these components is recommended.

In addition to the thermal effects of the arcs concerning the electrical circuitry conceivable cases have to be examined for mechanical consequences due to off normal loadings produced by non-regular, asymmetric current distributions and local weakening of the supporting structure due to thermal loading.

4.3 Coil Deformation or Displacement

In this section the mechanical consequences of electrical faults in the magnet system are described. Final aim is to quantify safety relevant large coil deformations or displacements or loss of integrity of parts of the coils or the coil supporting structures. This investigation should be performed in the near future dependent on the progress of the design.

The first step of the work done under this title was to find out those electrical faults which will yield the highest mechanical consequences for the magnet structure. To do such investigations first the transient currents initiated by the assumed faults have to be calculated for the magnetically coupled circuits. This is done using the code MSCAP [32]. After that the resulting forces on the coils due to currents in the magnetic field are determined using the code EFFI [33] which also serves to determine the magnetic fields and inductivity coefficients needed for MSCAP. Then, given the loading, the mechanical response of the structure of the magnets is evaluated using simple mechanical models. The results of these scoping calculating sometimes are confirmed by more detailed calculations applying the FEM-code ABAQUS [34].

In Fig. 11 the electrical and mechanical interactions of faults in different parts of the TF-coils and the PF-coils are summarized. Electrical faults in the TF coil system (e.g. a short of a TF coil) will strongly influence the current distribution in the TF coil circuit by electrical inductance and consequently the magnetic forces will change the loading conditions of the TF coil casing.

In a similar way faults in the PF-coil circuits strongly influence the currents of all PF-coil circuits and the magnetic force loading of the PF-coils.

But while (perfect geometry supposed) the electrical circuitry of the PF coils will not be influenced by faults in the TF circuits, the magnetic forces influence also the mechanics of the PF coils. The same is true considering faults in the PF circuitry. Thus, the mechanical consequences due to an electrical fault in one part of the system spread over all components. In reality this effect is even stronger, since TF coils and PF coils are partly coupled mechanically.

In Tab. 4-1 the characteristics of the mechanical consequences of faults in the magnet system are summarized. A fault in a TF coil circuit leads to additional inplane (ip) and out-of-plane (op) forces of the TF coils and furtheron will produce an op moment loading for the PF coils. (Under normal load conditions such moments do not occur.) Faults in a PF coil circuit will change the op and ip forces of the PF coils and, in addition, will give further op moments for the TF coils. As mentioned above, perfect geometry is assumed in our linear analysis. Imperfections lead to inductive coupling of all circuits and may also lead to stability effects which have to be analysed by nonlinear calculations. This may be the subject of future work.

In the following the results gained so far will be reported according to the paths described above:

- electrical faults in the TF-coils, mechanical consequences in the TF-coil structure,
- the same for the PF-coils,
- electrical faults in the TF-coils, mechanical consequences in the PF-coils, and vice versa.

Table 4-1: **Characteristics of the Mechanical Consequences of Faults in the Magnet System**

Location of Failure	Mech. Loading due to Electrical Faults on	
	TF Coil Casing	PF Coil
TF Coils	additional op*forces and ip**forces	op moment
PF coils	op moment	op forces ip forces

*op = out-of-plane
**ip = in-plane

4.3.1 Mechanical Consequences of Faults in the Toroidal Field Coils on its Coil Casings

The investigation of faults in the TF coil system reported in [24, 35, 36] lead to the result that a low ohmic short at a coil terminal will produce loadings for which the mechanical integrity of the central vault probably cannot be maintained. A similar conclusion can be found in [18].

In the past [35] different cases leading to non-homogenious loadings have been investigated. Some of those loading cases were due to the former NET-concept where the TF-coils did belong to two separate current circuits instead of one circuit as planned in the ITER concept. This change in design did reduce the number of fault scenarios and consequently the number of nonuniform load distributions. But the worst case, a low ohmic short circuit at the terminal of a TF-coil, still remains.

A further fault case, called open circuit mode, has been treated in [1] . Due to a quench in a coil and a subsequent arc or short at its terminal one coil is discharged while its neighbours have increased currents due to mutual inductance coupling. According to [1] the consequences concerning the central vault are comparable to the case of a short circuit.

The structural integrity of the TF coil system is dominated by the behaviour of the central vault composed by the wedge-shaped inboard legs of the TF coil casings.

Under operational conditions the centering forces of the coils wedge the inner legs together allowing for shear force loading due to friction between the insulated coil-coil interfaces.

At nominal loading the central vault is under a high rotationally symmetric compressive loading. In this case a vault is an optimum load-bearing structural component.

But faults in some coils will destroy this symmetry and as a consequence additional bending moments will have to be reacted by the vault. The interfaces are weak points from which the failure of the vault is inititated. Therefore the crucial details in estimating the load carrying capacity of the vault are the interfaces and not a very detailed stress distribution along the vault segments.

In the above mentioned calculations the force and stress distributions have been estimated by a simple ring model. Of most importance were the following failure criteria, which take into account not only the properties of the particular coil casings but also the nonlinear effects due to the interfaces between the coil legs:

1. Everywhere the stress σ must be lower than the yield stress σ_y or at least the ultimate tensile stress σ_{UTS}

$$\sigma < \sigma_y \text{ or } \sigma < \sigma_{UTS}$$

2. At all interfaces the normal stress σ_t must not be positive otherwise gaps would open up and failure due to instability would occur

$$\sigma_t < 0$$

3. At all interfaces the compressive hoop force F_h must allow for carrying the radial shear force F_s by friction

$$F_s < \mu F_h \quad (\mu = \text{friction coefficient at the interfaces}).$$

Indeed the above stated failure is not initiated due to violation of criterion ① limiting excessive stresses, but due to the violation of criterion ② or ③ which may occur even at low stress levels.

It might be argued that the shear keys at both ends of the ~ 15 m long central vault, which are designed to react the torsional loading of the vault due to the out-of-plance forces of the TF-coils, may also react the afore mentioned bending moments due to asymmetric fault loading of the vault. But the distance to the equatorial plane is too long as to prevent a failure initiation. However, it might be possible, that the shear keys can prevent a global failure of the whole coil assembly.

Concerning the safety considerations the type of failure mechanism is of some importance. As mentioned above a failure due to violation of criterion ② (gap opening) is a so-called unstable or catastrophic failure mechanism which has a potential to propagate suddenly into neighbouring components. This behaviour has been confirmed considering the vault under outer pressure as a nonlinear buckling problem [36]. Due to additional axial loadings the postbuckling behaviour of the vault modelled as a cylinder is stable. But if the interfaces are taken into account the vault is of the masonry arch type. Treating this problem by a nonlinear theory [36] the post-buckling behaviour changes to an unstable type. Furthermore it could be shown, that due to the interfaces a significant imperfection sensitivity is introduced. This means that imperfections due to geometry or loading (some fault loadings can be considered as load imperfections) reduce the critical buckling load, calculated without imperfections, considerably.

Because of the unstable failure behaviour it has been proposed to introduce an additonal locking along the whole coil legs [35, 36]. Otherwise experiments studying the nonlinear effects due to the gap behaviour, which have been proposed in [36] too, would be necessary.

4.3.2 Mechanical Consequences of Faults in the Poloidal Field Coils on its Coil Structures

Details of the results reported under this heading can be found in [37].

The fault scenario established for the PF coil system contains shorts in a single coil or a pair of coils and full voltage at the power supply of each of the seven PF-coil circuits. Due to the transient current program and the seven independent PF-coil circuits a great number of faults and fault combinations is possible. If in addition unsymmetrical plasma configurations (single null) are taken into account, as mentioned in [1], even far more extended fault scenarios are possible. In the work reported here 35 cases have been selected for analysis.

Some interesting results of the current calculations indicate that especially shorts in the solenoid coils lead to current ramps in the faulted coil or coil circuit and to opposing currents in its neighbouring coils. Similar results have been gained for the cases of full voltage. The quench is an important limiting effect in case of high currents and magnetic fields. Since the magnetic forces depend on these quantities their reliable determination is important for the subsequent calculation of sensible mechanical loadings. The quench analysis used here was based on assumptions which probably lead to pessimistic results concerning the consequent forces.

The loads have been calculated for times with maximum currents. In most cases these are the currents where quenching occurs. Due to the proportional dependence of the force on the current and the magnetic field this will usually lead to the maximum loads. But cases may exist where current combinations of the coils lead to higher forces due to a high magnetic field and lower currents. In addition the mechanical consequences may strongly depend on special load components and also on the load direction. Therefore it should be proven whether load combinations with higher mechanical consequences as the chosen cases do exist.

Depending on the support structures of the PF-coils three sub groups of the coils have been investigated:

a) solenoid stack
b) divertor coils
c) outer ring coils.

a) Solenoid stack

The solenoid stack consists of eight uniform coils held under precompression by tie rods. The stack is supported at the inner legs of the TF-coils in the shear key regions.

Concerning the vertical loads 13 cases out of 35 cases treated have been proven to be critical. The characteristics of these cases are very high forces directed away from the equatorial plane and also very high forces which press the coils together. In addition, the whole stack may have resulting forces which act on the supports at the TF-coils.

The coil stack under the different loadings has been investigated using a simple one-dimensional model which takes into account the precompression of the coil stack. The characteristic of this model is, that the system under precompression is statically indeterminated. But for some fault loading conditions the precompression is lost and the system changes its mechanical state to become a statically determinate one, sometimes with a decoupled subsystem. The physical meaning of this nonlinear system behaviour is, that if the precompression has been lost one or more gaps in the coil stack open up forming this new system or systems, respectively.

To evaluate the mechanical consequences of the described coil stack behaviour three failure criteria with different consequences have been established: Failure occurs if

(1) Gaps open up in the coil stacks (i.e. precompression is lost)

(2) the coil compression surpasses the yield strength in the coils

(3) the tensile stresses exceed the yield stress or the ultimate tensile strength in the supporting stack structure (tie rods)

Applying these criteria in 13 cases at least one failure criterion is met.

In all of these 13 cases precompression (criterion 1) is lost. The consequences are indifferent behaviour of the coils in case of minor horizontal loads. A higher precompression as used in the latest ITER-design helps in one case only. In a second case instead of criterion 1 criterion 2 is met.

Criterion 2 is met in two cases. In calculating the vertical stress it was assumed that only the steel fraction of a coil is load-bearing. The consequences will be plastic deformations and possibly a coil failure without greater consequences to the surroundings.

Concerning the failure propagation, criterion 3 is of most importance. In 4 cases the ultimate tensile strength of the tie rods is surpassed and the outward loaded coils will be accelerated to move outward unless the support design of the coil stack structure will hold the coils together. However a check of the actual support design revealed, that the clamping will not react these loadings and therefore will not prevent the coil movement. In two additional cases the ultimate tensile stress is not surpassed but the yield strength. This means that smaller displacements due to plastic deformation will occur such that at least precompression at normal loading will be lost.

Most of the inspected cases have an up down symmetry due to a fault concerning both coils of a PF-coil circuit. But this symmetry is destroyed for faults concerning just one coil. Of course, all PF coils as a whole must stay at equilibrium anytime. But the individual coil pairs will have resulting forces which act on the supportings at the TF-coil structure. Concerning the solenoid stack this means, that the stack support must react forces which are up to about 20 times the gravitational force of the whole solenoid stack. In the actual design the load-bearing capacity seems not to be sufficient and a failure with large displacements may occur. Furthermore it is important, that the resulting forces may be directed upward or downward according to the location of the faulted coil twin.

So far only the vertical loads and their consequences have been considered. The high fault currents produce also high radial forces and subsequent high tangential stresses in the coils. In one case the yield stress is surpassed in tangential direction in the faulted coil pair. But at the same time these coils are compressed in vertical direction beyond the yield stress.

Additional stress components due to a torsional loading around the solenoid winding pack will enhance the stress level.

b) Divertor coils

The divertor coils are attached to the TF-coils at their upper and lower arches. In the actual design the clamping is able to react the vertical loads. Just in one case the radial load is leading to hoop stresses beyond the yield stress. This will lead to plastic deformations, but only low displacements.

c) Outer ring coils

The outer ring coils, consists of two coils of the same diameter coupled by an intercoil structure hung up by pins fixed at the outer TF-coil legs. In two cases the hoop stress exceeds clearly the ultimate tensile stress for coil PF6 and PF7, respectively. In one case the coil PF7 is under a compressive hoop stress loading. But the buckling of the coil is avoided due to the vertical brackets of the coil support structure which act as an elastic foundation for the ring coil.

The vertical loading can be reacted by the supporting structure and the clamping at the TF-coils for all investigated cases.

A failure of the outer ring coils due to the overstress, discribed above, would lead to bursting of these coils and subsequent large deformations and possible failure propagation to components outside the magnet system.

Now, having seen some quite severe mechanical consequences it will be worthwile to check, whether the severe mechanical consequences obtained above can be avoided by design modifications. The catastrophic failures of the solenoid stack can be avoided if the cross section of the tie rods is enlarged by a factor two. The factor 2.5 could even bring the tension stress below the yield stress. In addition the coil stack support should be slightly reinforced to react vertical forces of the coils in some cases. A formlocking between the individual coils of the stack would prevent uncontrolled horizontal coil displacements when the precompression of the coil stack is lost. The remaining failures occuring at the solenoids would then be of tolerable type.

As to the severe failures of the outer ring coils the load-bearing steel cross section has to be enlarged by ~ 20 % for the PF6 coils and ~ 60 % for the PF7 coils. Thus the catastrophic failures of the PF-coil casings due to faults in the PF-coil circuits can be avoided.

4.3.3 Mechanical Consequences of Interactions Between Poloidal and Toroidal Magnets

To analyse the mechanical consequences in the TF-coil structure caused by electrical faults in the PF-coil circuits and vice versa the same fault scenarios are underlaid as used in the previous sections. Details about these investigations can be found in [38].

a) Mechanical consequences in the TF-coil structure due to faults in the PF-coil circuits

Under normal current distribution in the TF-coils (i.e. each TF-coil has the same current) the out-of-plane forces of the TF-coils are produced due to the PF-coil current program. Having an up-down anti-symmetric distribution the out-of-plane forces act as an out-of-plane moment.

Under PF-fault conditions this is not changed principally, but the forces and the moments can be much higher. The force distribution along the perimeter depends on the different currents of the PF-circuits.

Concerning the central vault the out-of-plane moments produce a torsional loading, twisting of the vault, which can be considered as a slotted tube. At the interfaces of the slots an axial shear stress distribution is produced which must be reacted by friction forces and the shear keys at both ends of the vault.

Rough evaluations for a quick overview of all the cases of the fault scenario have been done using a simple model considering the vault as a flexibel pipe with stiff shear key regions at both ends.

Under normal loads (normal out-of-plane loading due to the nominal current program during a burning cycle) the shear stress distribution is relatively low at half the tube length and increases at both ends. The hoop stress due to the nominal radial TF-coil loading allows for friction locking except at the ends where shear keys carry the higher shear loading.

For several fault cases high shear stresses occur at midlength of the vault, and therefore the legs at increasing fault loading suddenly will slip and the shear forces will upruptly load the shear keys. Along the interfaces where the slip occurs the individual coil legs will be stressed due to increased bowing and individual torsion since the torsional stiffness of the vault decreases also upruptly.

It remains to prove, if the shear keys can react such a dynamic loading which the coil legs undergo. On the other hand the additional locking along the whole length of the coil legs proposed in section 4.3.1 would solve this problem, too.

Considering the upper coil arches between the stiff shear key regions and the outer intercoil structures the increased out-of-plane loading due to faults of the PF-coil circuits will stress these parts in addition. Now the coil arch can be treated as a curved beam which undergoes torsion and bending. Compared to normal loading, under fault conditions the loads can roughly grow by the factor two at maximum.

The resulting stresses are relatively low for all cases and the peak values of the different stresses due to bending, torsion, and shear occur at different locations. So far, the details of the coil leg cross section did not have been taken into account.

If the bolted and welded joints combining the two coil casing halfs are taken into account, the shear stresses at the interfaces have to be reacted by the bolts and the welding seam. A rough calculation, considering the shear load carrying capacity of the bolts, revealed that at the upper arch some bolts are strongly loaded even under nominal conditions. They hardly are able to carry the fault loading. Therefore, increased out-of-plane displacements which again will lead to an increased out-of-plane loading due to the decreasing distance to the neighbour coil (similar to magnetoelastic buckling) and subsequent nonlinear failure cannot be ruled out.

Therefore this part of the TF-coil casing should be taken into a closer inspection to avoid the described instability.

b) Mechanical consequences in the PF coil structures due to faults in the TF-coil circuit

Faults in the TF-coils lead to asymmetrical toroidal fields which yield overturning moments for the PF-coils around a line through the faulted TF-coil and the central point of the coil assembly and resulting in-plane forces perpenticular to this line.

Under such loadings the solenoid coil stack undergoes a bowing. But the maximum bending stresses are still tolerable. Due to the lateral in-plane forces the friction between the piled solenoids cannot avoid smaller lateral displacements limited by the surrounding tie rods. If this cannot be tolerated a geometrical locking between the individual coils, just proposed in the previous section treating the PF-fault loadings, should be introduced.

At last critical point is the supporting of the pair of outer ring coils hung up at the outer TF-coil legs. Due to the asymmetrical out-of-plane loading (which yields the overturning moment) the 16 bearing blocks are loaded very unequally. The supports sitting on the TF-coils neighbouring the faulted coil have by far the highest loads. In one critical case the screws of the mentioned bearing boxes would not withstand the loads. Therefore the supporting should be reinforced.

4.4 Volume Change of Cryogenic Helium

The main focus of the assessment of the consequences of this event is the possible pressure impact to radioactivity confining structures, especially the vacuum vessel.

The helium inventory in the coils amounts to about 80 m^3. The maximum portion in one coil is about 8 m^3, and this applies for PF6. Each TF coil contains about 2 m^3. Additional inventories are present in the supply lines and refrigerating plant.

Volume changes of cryogenic helium may be initiated mainly by two different reference accident sequences as mentioned in chapter 3: Loss of insulation vacuum accident (LIVA) and Loss of coil cooling accident (LOCA).

A LIVA may be initiated by a breach in the cryostat vacuum boundary or a LOCA in a cooling pipe within the cryostat. A LOCA may be initiated by a break of a helium line or a leak of a coil due to extended arcing.

In both cases the helium expelled from a coil into the cryostat is heated up by the Joule effect due to the coil quench, by the structural masses, and by arcing if an arc occurs. Both, the fraction of helium inventory that is prone to expulsion and the amount of energy that can be transferred to the helium and that influences the expulsion dynamics need further investigations.

It is assumed in [18] that in the case of a cooling line break helium may be expelled into the cryostat. The time of expulsion could approach the time of a coil self quench which is about 30 s. The maximum quantity of helium in one coil is estimated to pressurize the cryostat with a volume of 6000 m^3 to 30 kPa at 300 K. This pressure lies far below the design pressure of the cryostat. As a mitigating measure bursting disks opening a pressure relief volume could be provided additionally.

In contrary, other assessments for NET [39, 40] indicate that with certain assumptions concerning the amount of expelled helium and the heat inputs to the helium both for a LIVA and LOCA accident the overpressure in the cryostat could exceed the design limit.

As already mentioned, further investigations of these phenomena will be necessary in parallel with the evolving design.

With regard to the cryogenic system itself a recent review on operating experience of cryogenic systems for different applications has been compiled by L.C. Cadwallader [41]. In this report estimates of cryogenic component failure rates and accident initiating event frequencies are presented for use in risk assessment, reliability, and availability studies. Safety concerns with cryogenic systems are discussed in order to identify possible weak points.

5. Conclusions and Recommendations for Further Analyses

5.1 Identification and Analysis of Most Important Safety Concerns

The induced radioactivity in the magnets is small. However, the large amount of stored energy within the coils is considered to be a potential hazard by the possibility to initiate or enhance magnet failures. A still open question to be investigated is whether faults in the magnets may have the consequence that the containment function of an adjacent component is lost. Mechanisms that may lead to a failure are mechanical or thermal electrical impacts or a combination of both.

At KfK a wide spectrum of magnet accidents has been investigated theoretically and experimentally. A short summary of the results is given here.

With respect to safety questions comprehensive experimental investigations on the TESPE torus and corresponding analyses have been performed in order to identify the most relevant faults in TF coil systems. For this part of the safety studies it was assumed that a certain failure has happened and its safety consequences were investigated.

It could be shown that each of the following single events can be taken without safety relevant damage by the magnet system being appropriately designed: Loss of cooling, loss of insulation vacuum and magnetic buckling. Their significance grows in case of simultaneous occurrence of further faults like local damage of electrical insulation outside of the magnets.

However, there are two major faults which had to be studied in more detail due to their safety relevance, namely short-circuits and electrical arcs. Arcs may occur inside or outside of magnets, they may burn in parallel to an inductance or in series. As the environmental conditions (such as magnetic field, various materials as heat sinks, melting and evaporation of materials, gas streams, surface geometry) have a significant influence on the current-voltage characteristics of the arcs, an extensive experimental program was performed. Good reproducibility was found when the environmental conditions were kept. Depending on the conditions values of the burning voltage were found between 20 and 200 V at the currents available in the experiment. This reproducible data basis can be taken for assessing corresponding values by law of similarity. For instance, a 40 kA / 20 mm arc corresponds to a voltage of 100 to 400 V. With these values the current distributions in the system and the energy deposition were calculated.

In case of of an arc parallel to one coil of the TF system of NET a maximum of 6.7 GJ may be burned in the arc, if there would be no other mechanism of energy distribution like loss of insulation vacuum and quenching. In order to have an idea of the amount of material involved a figure of 3 MJ/kg of winding can be used (all material is melted and half of it is evaporated). Again without taking into account the energy distribution mechanisms, more than 80 % of the total 42 GJ stored in the NET TF system may be set free in an arc burning in series if the unaffected circuit of the two TF circuits can be discharged only. This maximum figure reaches 100 % in case of a single coil circuit and malfunction of all discharge circuits. But even in case of a fully working discharge circuit the deposition of energy still amounts on several 100 MJ. Practical measures for stopping burning of an arc do not exist. These energy values show clearly the significance of the electrical arcing in the magnet system. Safety relevance can be seen e.g. when a series arc burns to such a length that neighbouring sensitive components are closer than the arcs electrodes, or when a gas stream takes the arc to other components, or when the magnetic field drives the arc, etc..

It could be shown that the ignition of an arc through burning of a short during charge or discharge cannot be avoided by reducing the driving voltage even to an arbitrary low value. The arc cannot be stopped and the coupled-in energy cannot be extracted.

While the significance of electrical arcing could be demonstrated it should be also made clear that appropriate system design will be capable of handling these questions. However, it is necessary to assist the designer by investigating in more detail the precursors of the named faults, to find more mitigating measures, and have a detailed analysis of the reference accident sequence as proposed.

The question of missile generation is under investigation. The status of work is encouraging as the new results obtained so far lead to dramatically lower conversion of magnetic energy to kinetic energy than assumed till now.

To analyse thermal failure events the modular code system MAGS has been developed. MAGS has the capability to describe all essential effects of this events, i.e.

- Simulation of coolant plena

- Thermohydraulic analysis of the coolant with SARUMAN

- Thermal analysis of the solids

- Quench detection and transient quench resistance calculation

- Current calculated with MSCAP

- Magnet field calculated with EFFI

As sample cases a quench evolving at the operational current as well as the quench of a shorted TF coil during the dump of the TF coil system were investigated.

We found:

- Importance of local magnet field on quench velocity

- Importance of helium plena for quench propagation

- No local hot spot during quench

Subject of structural analyses was the evaluation of the consequences of faults in the electric systems on the magnetic loading and the mechanical response of the structures.

The ITER magnet system consists of two coil subsystems: The TF coils electrically connected in one circuit and the PF coils with seven circuits containing a pair of coils each. Mechanically the substructures are the 16 TF coils the inner legs of them forming the central vault, the central solenoids combined in a coil stack, the divertor coils and the outer ring coils.

According to the different fault locations a systematic study on the spread of the mechanical consequences on the subsystems has been performed. Then a fault scenario for the different circuits with different fault modes (short circuit, erroneous control) has been established containing about 40 fault cases. The transient currents of the circuits coupled inductively have been determined and the magnetical loadings on the coils have been calculated for all cases. The principal mechanical behaviour and the relevant failure mechanisms of the complex structures have been evaluated using simple, transparent models. The results have been confirmed for critical cases by FEM calculations.

Several parts have been identified leading to structural failure under fault loading conditions. In terms of safety analysis there are two failure categories: tolerable failure, where the damage is confined to the magnet system and severe failure, typically being of unstable kind and possibly impairing neighbouring radioactivity confining components. The following critical items are of the latter type where with the actuel design concept a loss of integrity could be initiated:

- Local instability of the central vault in the equatorial plane under radial bending moments due to TF coil faults

- Loss of torsion rigidity of the central vault under increased torsional loading due to PF coil faults

- Failure of the coil case bolts and subsequent large unstable lateral displacements at the upper TF coil arches due to increased out-of-plane loads under PF coil faults

- Rupture of the solenoid stack structure caused by strong repelling forces due to PF coil faults

- Rupture of outer ring coils under excessive hoop stresses due to PF coil faults.

To avoid these failures proposals for an improved design have been made. The failure of the first three items does not occur due to excessive stresses in the components but is initiated at the interface areas of the composed structure. Sometimes theses interfaces are needed for electrical insulation. The proper design of such interface connections is of more principal nature and should be investigated in parallel to the designers work.

5.2 Open Questions and Recommendations for Further Analyses

As a basic design requirement of the NET/ITER magnet system it was assumed that any fault and related damage should be confined within the magnet system without jeopardizing adjacent components. The assessment of the extent to which this requirement can be fulfilled is a major objective. Hence, further analyses will concentrate on reference accident sequences, including events which have a potential to propagate from the magnet system to adjacent components.

The following events are considered to have a potential of failure propagation:

- Uncontrolled growing of a normal conducting zone
- Electric arc outside a coil
- Electric arc inside a coil
- Coil deformation or displacement
- Volume change of cryogenic helium.

5.2.1 Uncontrolled Growing of a Normal Conducting Zone

The previous investigations have shown the importance of the local magnetic field on the velocity of a quench propagation and the importance of the helium plena. Pressure peaks of the helium in the cable during the quench process will need further analysis.

The progam system MAGS being a modulare system offers a flexible range of application. Some code improvements and verification efforts are recommended.

5.2.2 Arc Outside a Coil

An arc outside of a coil may occur at the bus bars of a coil. Initiating events may be either a quench inside the coil or a direct failure at the bus bars. If an arc burns there the arc will be pressed to the vacuum duct of the vacuum vessel due to the magnet field and may melt a hole in this component. This will lead to a 'loss of vacuum' event being a reference accident sequence of NET/ITER.

5.2.3 Arc Inside a Coil

As the experiments have shown even in a TF coil an arc will propagate primarily in circumferential direction due to the toroidal magnet field. If we assume that an arc occurs at the outermost pancake then the magnet field presses the arc to the coil casing. After some time a hole may be burnt into it. Through this hole the arc can reach also other systems if the distances are small enough. Such a situation can be imagined in the upper connection box where all coolant and tritium lines to and from the vacuum vessel are accumulated.

Aim of the analysis proposed is to find out energies consumed resp. available at the time when the coil case is locally molten, the size of the hole and, depending on that, how far such an arc may reach.

5.2.4 Coil Deformation or Displacement

As stated above the central vault could become unstable locally for some fault loading cases. Then the shear keys at both ends of the central vault have to maintain the global stability of the whole assembly of the magnets. If they fail too, which remains to be investigated, the coils will move. It is then of most concern whether the radioactivity leading pipes of the blankets will withstand such displacements without rupture.

Large lateral displacements of the upper arches of the TF coils will impact the upper connection box containing most of the piping to and from the vacuum vessel. Since the arch failure is of unstable type, due to the increasing loads with growing displacement, more detailed investigations will be needed.

Rupture of solenoid stack tie rods may lead to uncontrolled vertical coil movements hitting against the cryostat vessel above and below to the coil assembly.

Bursting of the outer ring coils may impact the cryostat sidewall by coil fractions.

5.2.5 Volume Change of Cryogenic Helium

Volume change of cryogenic helium with the possible consequences of an overpressurization of the cryostat and an impact on the vacuum vessel need further investigations. On the other hand, gas entry into the cryostat may have an influence on the quench propagation of the coils. This is a desired effect directed to inherent safety.

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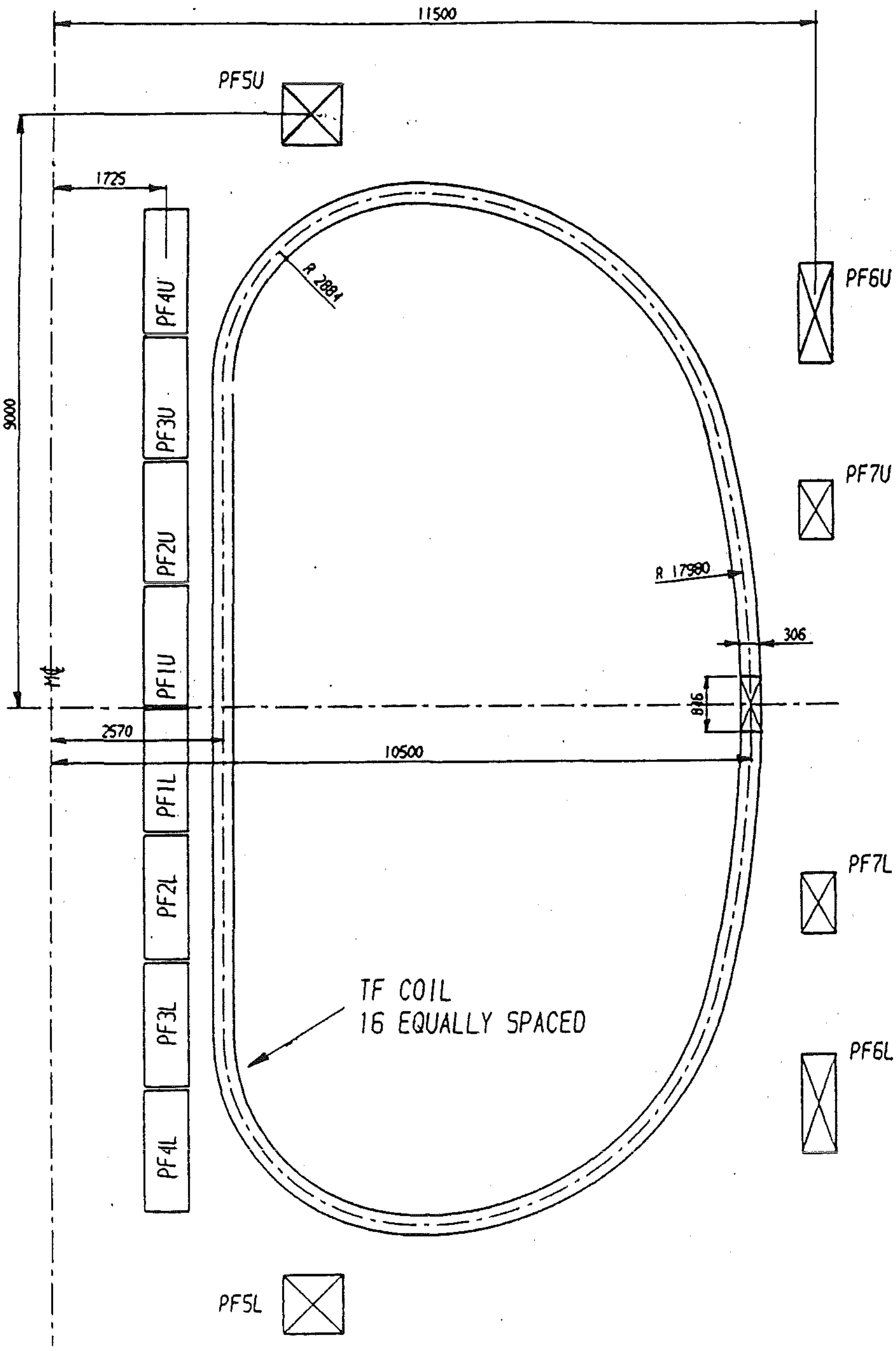


Fig. 1: Arrangement of the TF and PF Magnets for ITER [1]

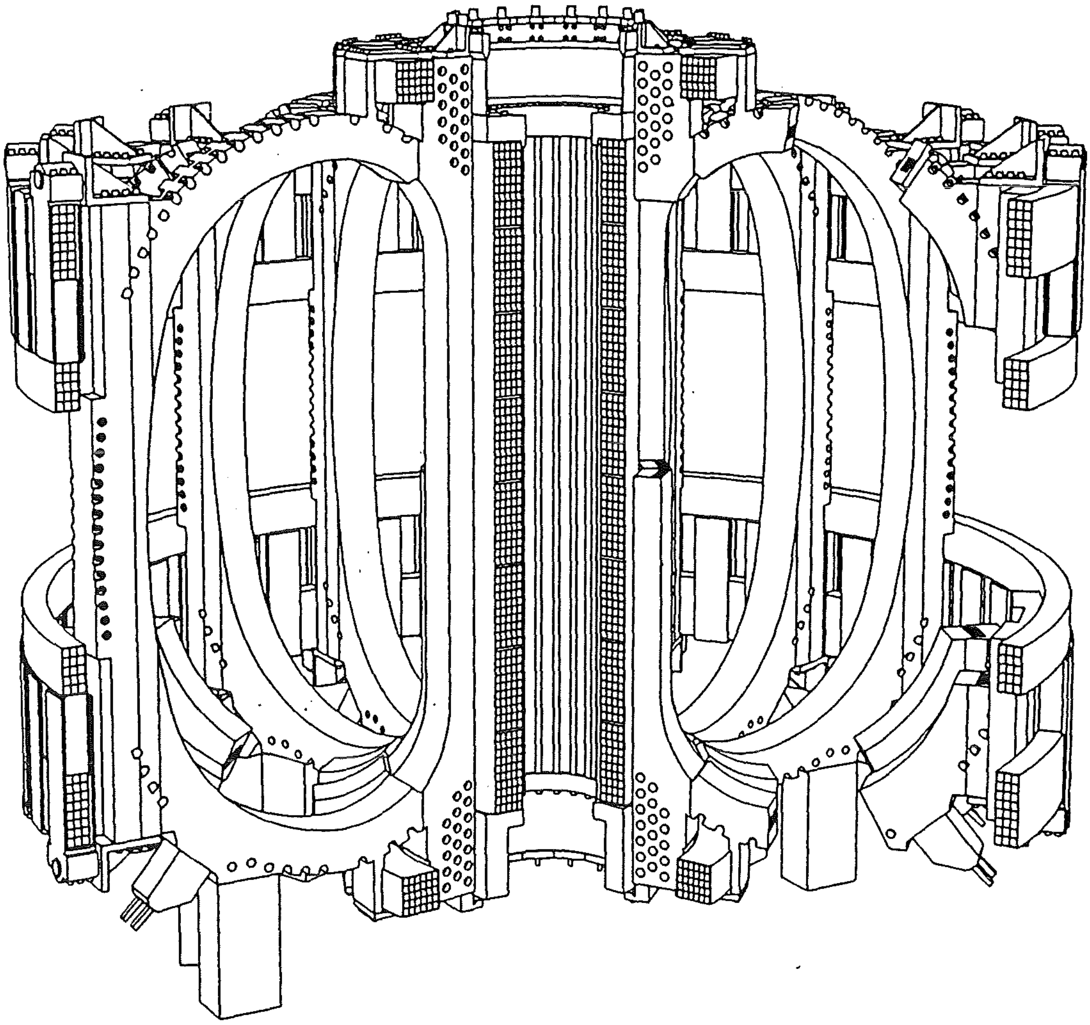


Fig. 2: Cut Away View of Magnetic System [1]

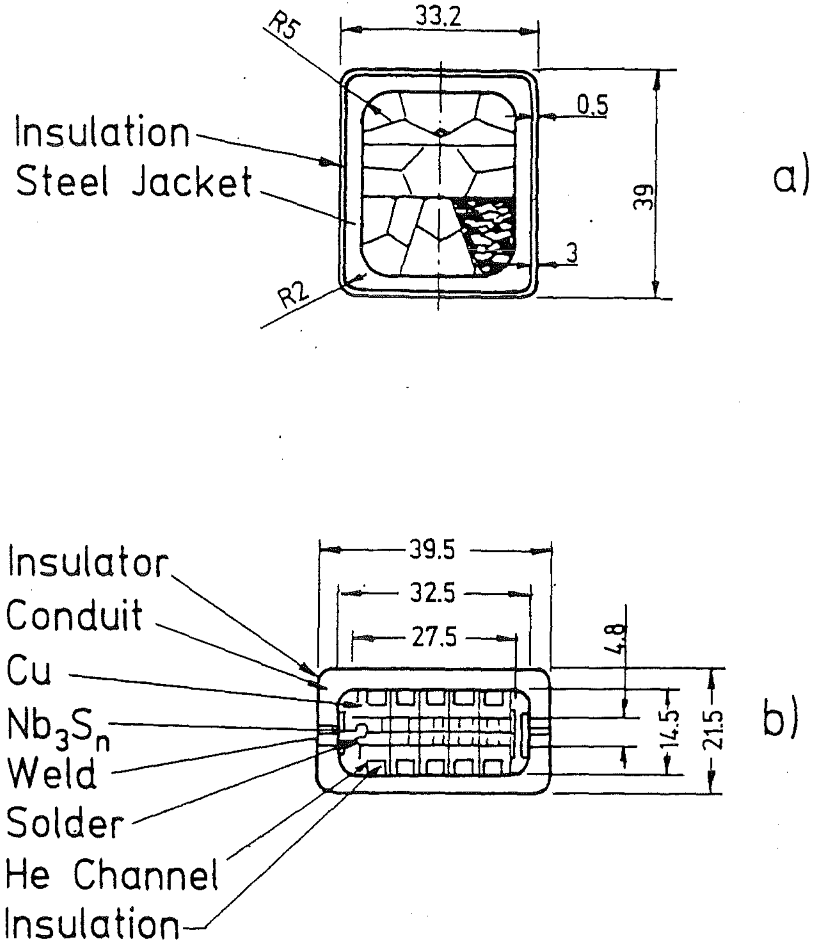
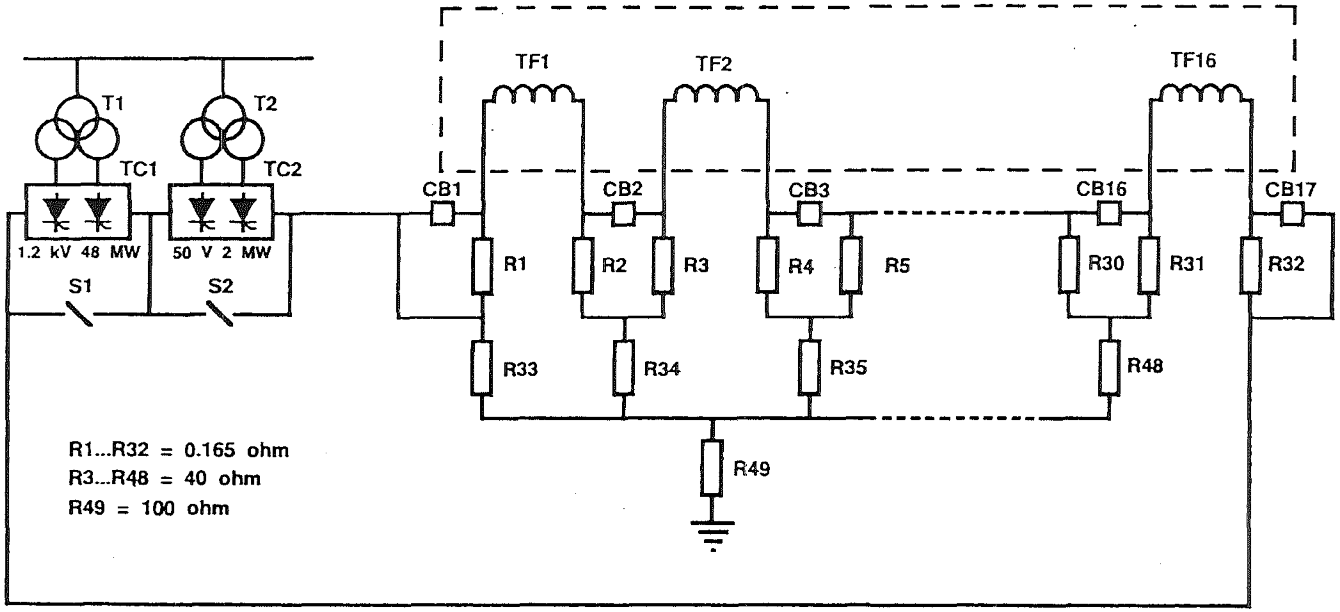


Fig. 3: Configuration of a Cable-in-Conduit (a) and a Monolithic (b) Nb_3S_n Conductor [1]



Legend:

TF = TF coiL
R = Resistor
CB = Circuit Breaker
T = Transformer
TC = Thyristor Convertor
S = Switch

Fig. 4: TF Power Supply and Protection [1]

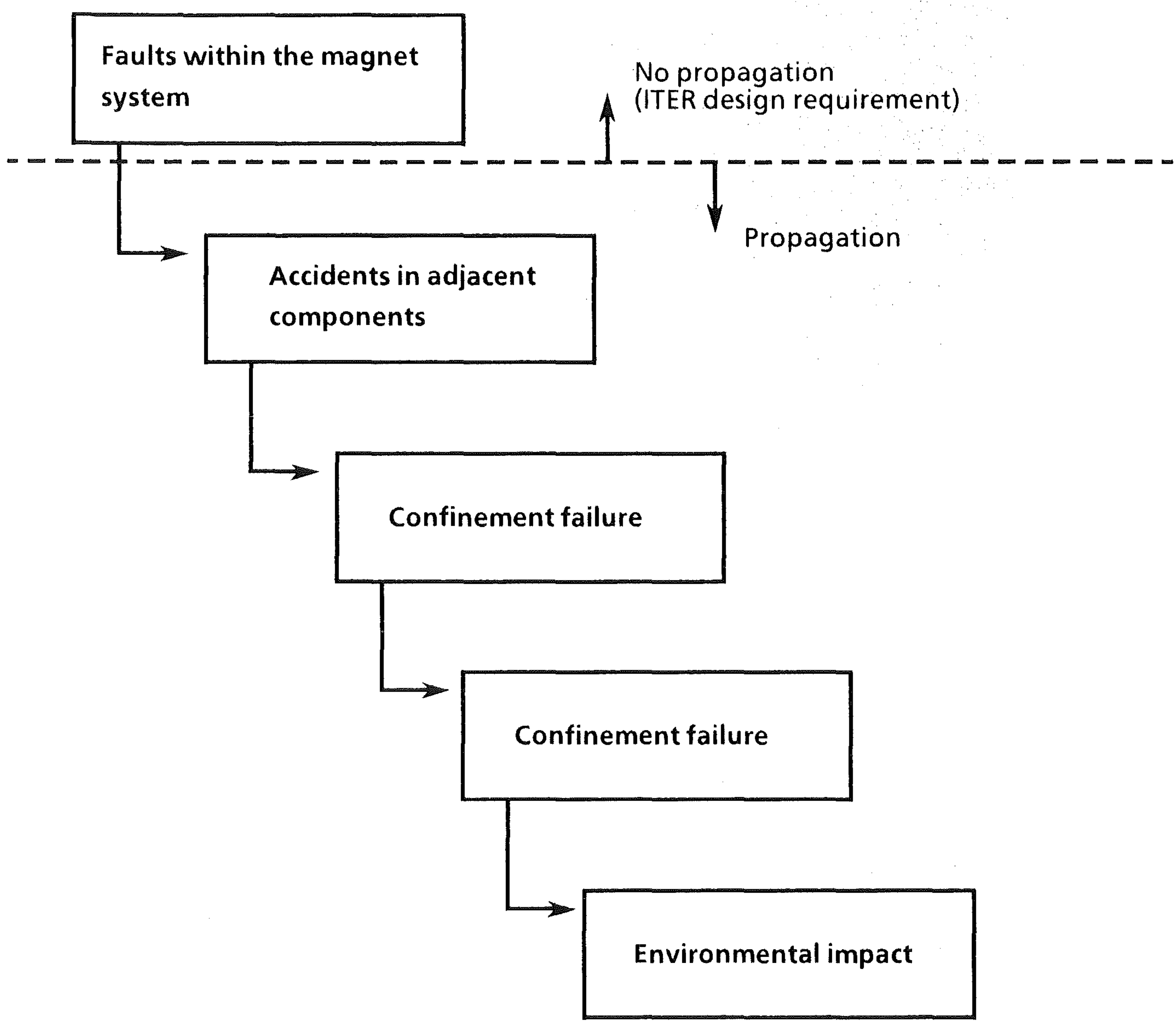


Fig. 5: Coarse Representation of a Conceivable Failure Propagation

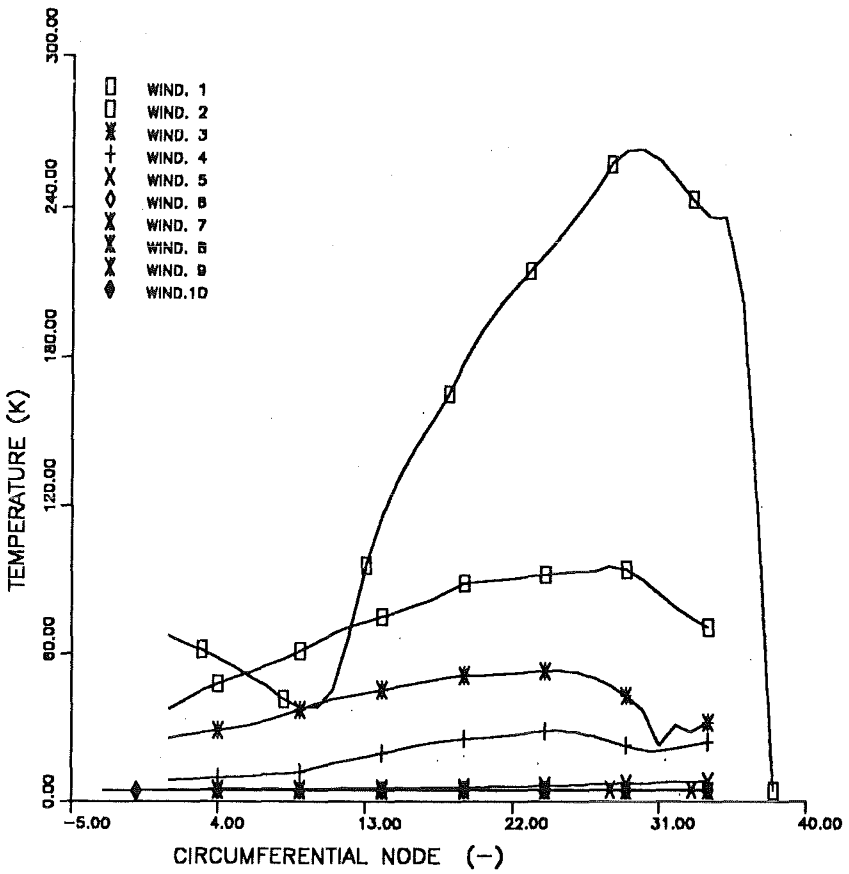


Fig. 6: Temperatures in Pancake 1.
Data plotted versus the circumference, 7.5 seconds after quench initiation

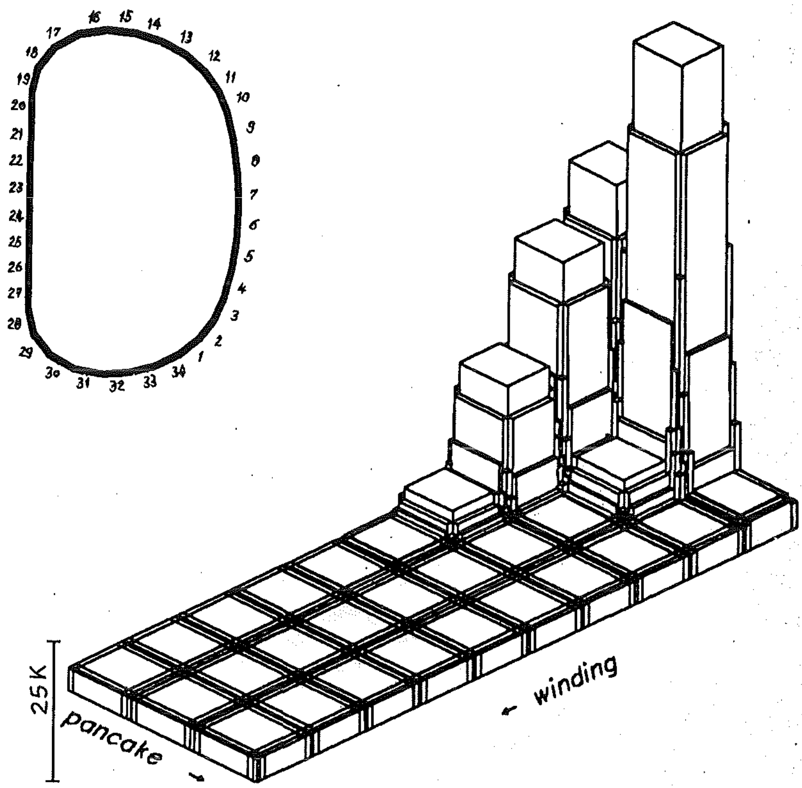


Fig. 7: Temperatures in Cross Section 4,
7.5 seconds after quench initiation. Maximum temperature is 87 K.

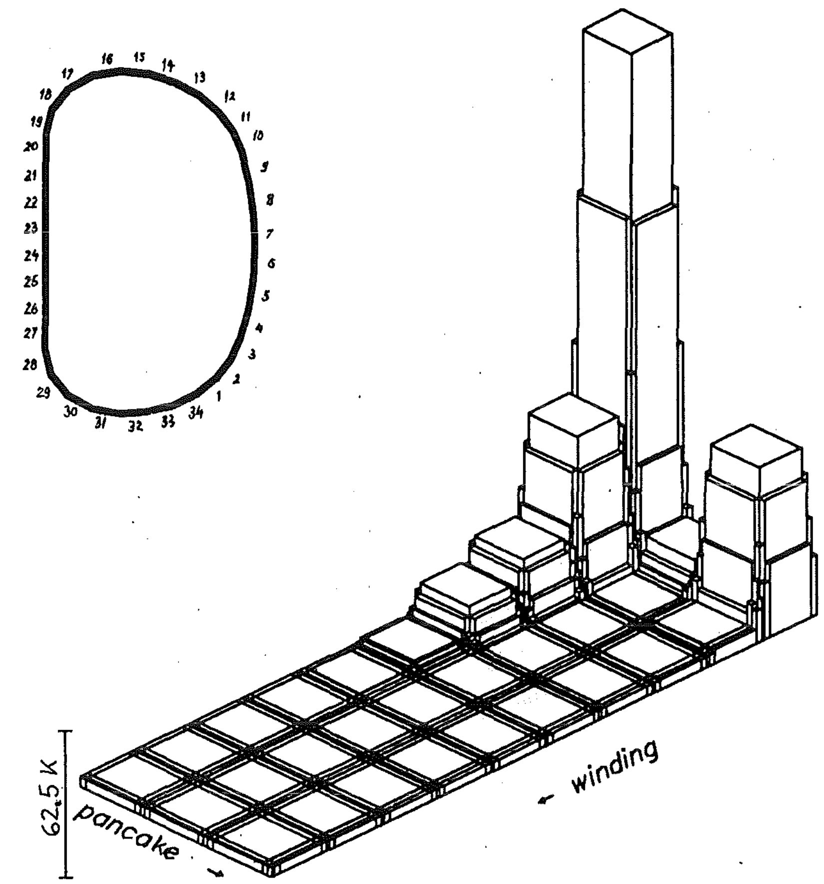


Fig. 8: Temperatures in Cross Section 32,
7.5 seconds after quench initiation. Maximum temperature is 250 K. The highest temperatures are found in the cable space zones. They are surrounded by jacket temperatures and the jackets are surrounded by insulation.

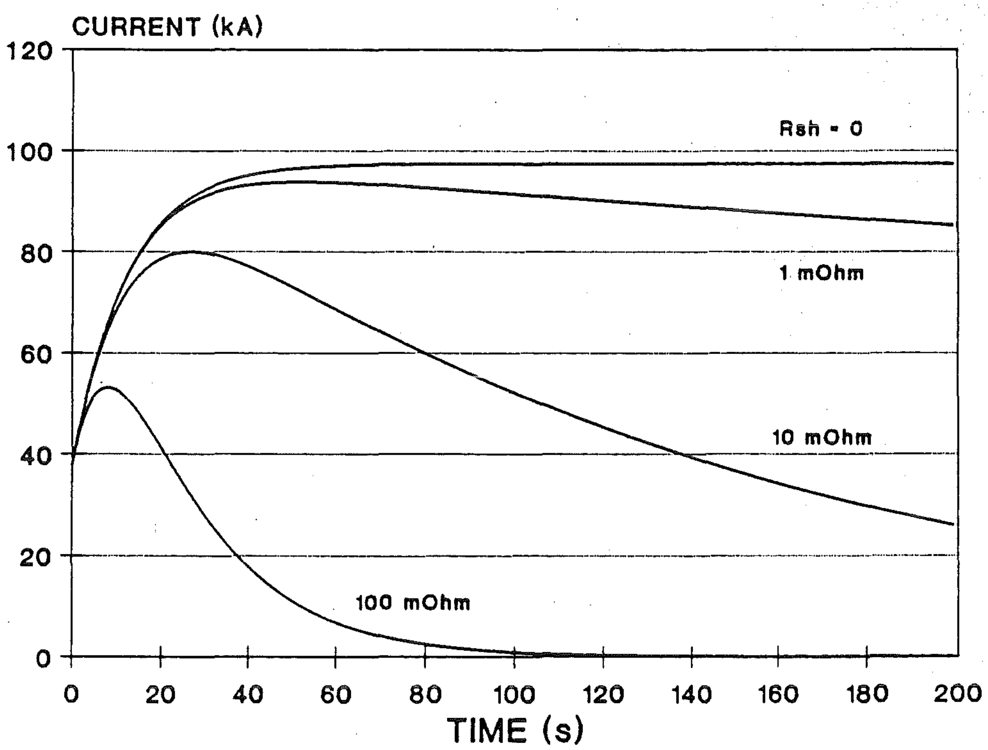


Fig. 9: Influence of the Short Resistance on the Current in the Shorted Coil of the TF Magnet Systems of NET/ITER During Discharge with a Total Resistance of 4 Ω

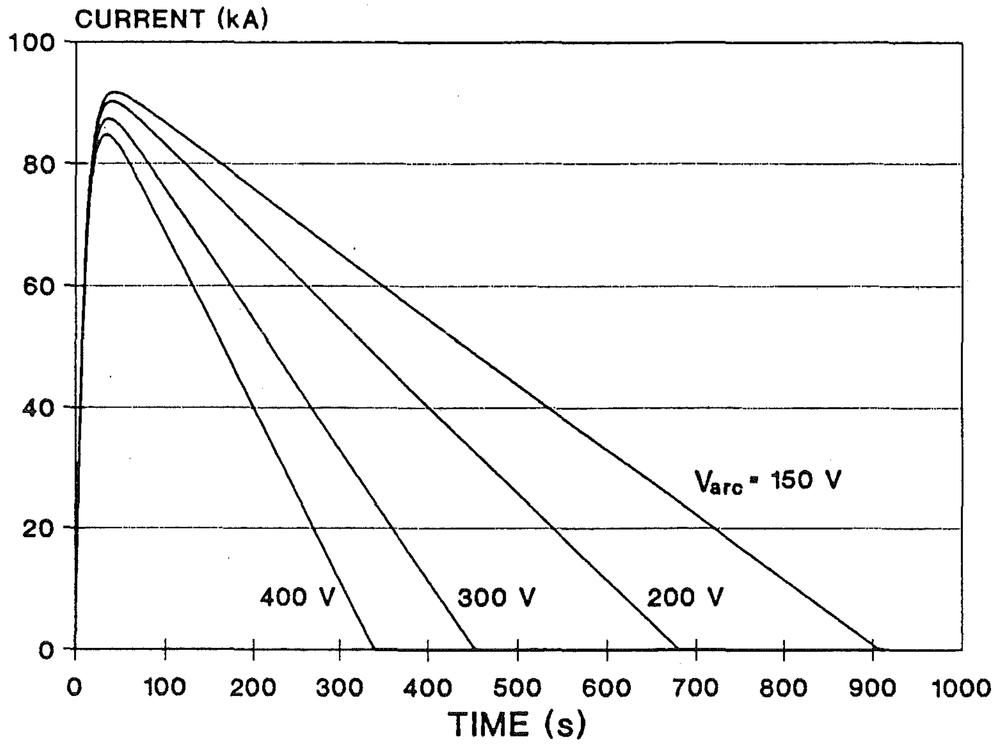


Fig. 10: Influence of the Arc Voltage on Current and Burn Time of the Arcing Coil of NET/ITER TF Magnet Systems During Discharge with a Total Resistance of 4 Ω

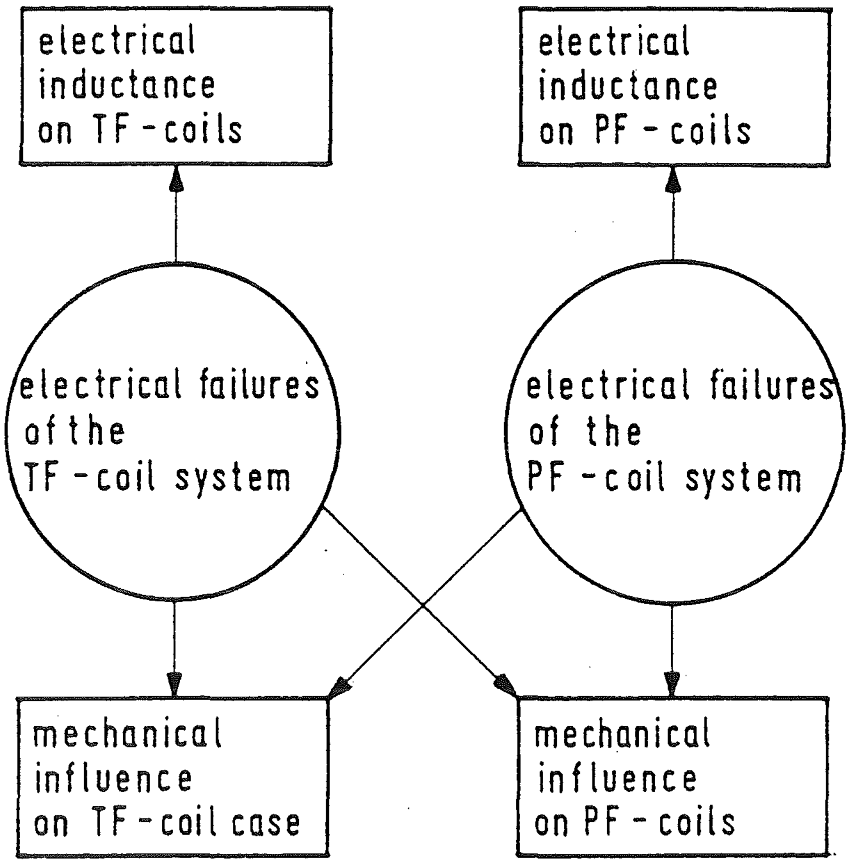


Fig. 11: Electrical and Magnetic Interactions of Electrical Faults in the Magnet System