126
4/3/84
PPPL-2083

UC20-E

①

DR-2208-X

PPPL-2083

J-13976

NOTICE
REPRODUCTION OF THIS DOCUMENT
It has been reported that there is no
available copy to permit the best
possible availability.

SAFETY ASSESSMENT
FOR THE
S-1 SPHEROMAK

Edited by:

R. Ellis, Jr. and J.R. Stencel

FEBRUARY 1984

MASTER

PLASMA
PHYSICS
LABORATORY

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

PRINCETON UNIVERSITY
PRINCETON, NEW JERSEY

PREPARED FOR THE U.S. DEPARTMENT OF ENERGY,
UNDER CONTRACT DE-AC02-76-CBO-3073.

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

SAFETY ASSESSMENT DOCUMENT
FOR THE
S-1 SPHEROMAX

FPPL--2083

DE84 010234

S-1 Co. Head, M. Yamada 12/21/83

S-1 Co. Head, R. Ellis, Jr. 12/20/83

APPROVALS

S-1 Engineering Manager 12/20/83
A. Janos

DSO Technical Operation 12/20/83
E. Simon

Occupational Medicine & Safety
H. Howe

Mgr. Project and Operational Safety 12/20/83
J. Stencel

REVISION NO.	REVISION DATE	APPROVAL SIGNATURE

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

4B

TABLE OF CONTENTS

	<u>Page</u>
1.0 INTRODUCTION AND GENERAL DESCRIPTION OF THE PROJECT.....	1
1.1 Introduction.....	1
1.2 Goals and Objectives.....	2
1.3 Participants in S-1 Design, Construction, and Operation.....	2
1.4 Summary of Significant Items.....	3
2.0 SUMMARY SAFETY ANALYSIS.....	4
2.1 Hazards.....	4
2.2 Fire Safety.....	8
2.3 Property Damage.....	10
2.4 Explosion and High Pressure Safety.....	10
2.5 Natural Phenomena.....	11
2.5.1 Earthquakes.....	11
2.5.2 Tornados, Extreme Wind.....	12
2.5.3 Floods.....	12
2.6 Noise.....	12
3.0 SITE	12
3.1 Location.....	12
4.0 FACILITY AND PROCESS DESCRIPTION.....	12
4.1 Experimental Area.....	12
4.2 Power Supplies.....	14
4.2.1 General Description.....	14
4.2.2 Poloidal Field Power Supply System.....	14
4.2.3 Toroidal Field Power Supply System.....	15
4.2.4 Equilibrium Field Power Supply System.....	15
4.2.5 Switching Modules.....	16
4.2.6 Electrical Bus.....	17
4.2.7 Charging Supplies.....	17

TABLE OF CONTENTS (CONT'D)

4.3	S-1 Device.....	18
4.3.1	Coil Systems.....	18
4.3.2	Vacuum System.....	20
4.4	S-1 Operating Control.....	23
4.4.1	Introduction.....	23
4.4.2	S-1 Safety System.....	24
4.4.3	Emergency Shutdown.....	26
4.4.4	EF Control System.....	27
4.4.5	PF/TF Control System.....	30
4.4.6	Vacuum System.....	33
4.4.7	S-1 Water Control and Monitoring.....	35
4.4.8	S-1 Computer and Man-Machine Interface.....	36
4.4.9	Grounding.....	38
4.5	Fire Protection.....	48
4.5.1	Fire Protection System.....	48
4.5.2	Fire Fighting Personnel and Equipment.....	49
5.0	HAZARD ANALYSIS.....	50
5.1	Accident Analysis.....	50
5.2	Failure Mode Analysis.....	50
6.0	QUALITY ASSURANCE.....	50
7.0	CONDUCT OF OPERATIONS.....	51
7.1	Organization.....	51
7.2	Training.....	51
7.3	Testing.....	52
7.4	Configuration Control.....	52
7.5	Procedure.....	52
7.6	Safety Review Systems.....	52
7.7	Emergency Planning.....	53
8.0	ACKNOWLEDGMENTS.....	53
9.0	REFERENCES.....	54

TABLE OF CONTENTS (CONT'D)

LIST OF TABLES

<u>Table No.</u>	<u>Title</u>	<u>Page</u>
1	Hazard Evaluation and Design Provisions.....	57
2	Toroidal Field Winding Parameters.....	58
3	Poloidal Field Winding Parameters.....	59
4	S-1 Equilibrium Field Coil Data.....	60
5	Accident Modes.....	61
6	Accident Modes.....	62
7-18	S-1 Failure Analysis Modes.....	63-74
19	S-1 Post Operational Phase - Assurance Controls.....	75

TABLE OF CONTENTS (CONT'D)

LIST OF FIGURES

<u>Figure No.</u>	<u>Title</u>	<u>Page</u>
1	S-1 Floor Plan (Ground Level).....	76
2	S-1 West Elevation.....	77
3	S-1 Spheromak Cut-A-Way View.....	78
4	Cross Section of Flux Core.....	79
5	Flux Core Winding Schematic.....	80
6	S-1 Control System (CAMAC).....	81
7	PF/TF Crate.....	82
8	MG Crate.....	83
9	Interlock Layout.....	84
10	Kirk Key System.....	85
11	Safety Lockout Switch ("Grove Switch").....	86
12	EF System Configuration.....	87
13	Capacitor, Filter Location (MG Area).....	88
14	EF System Block Diagram.....	89
15	EF State Diagram.....	90
16	PF/TF Power Supplies.....	91
17	PF/TF System Block Diagram.....	92
18	PF/TF State Diagram.....	93
19	S-1 Pumping System Schematic.....	94
20	Water Valve Control.....	95

1.0 INTRODUCTION AND GENERAL DESCRIPTION OF THE PROJECT

1.1 Introduction

The S-1 machine is part of the Magnetic Fusion Program. The goal of the Magnetic Fusion Program is to develop and demonstrate the practical application of fusion. S-1 is an experimental device which will provide an essential link in the research effort aiming at the realization of fusion power. The advantages of fusion power often stated are

- a. Inexhaustible, low cost fuel;
- b. Fail-safe reactor operation;
- c. Absence of weapons application;
- d. Nonradioactive combustion products.

An experimental device - such as the S-1 - has the following role in developing a fusion reactor

- a. It facilitates the understanding of the underlying theoretical and experimental principles of plasma physics.
- b. It permits the development of new ideas and new directions in advancing the application of scientific principles.
- c. It serves as a proving ground of theories.
- d. It functions as a teaching tool to train research and operating personnel.
- e. It allows the development of engineering methods related to power pulses in a reactor relevant application.

This report was compiled as a summary of the analyses done to ensure the safe operation of S-1. This report meets the requirement of the Princeton Plasma Physics Laboratory Health and Safety Directives, specifically HSD-5003¹ and DOE Orders 5481.1A,^{2,3}

1.2 Goals and Objectives

The S-1 Spheromak is a research device dedicated to experiments that will allow researchers to address the essential aspects of the Spheromak configuration, such as quasi-static formation, ideal and resistive MHD stability, and plasma energy confinement.

To support the above goals the following objectives need to be accomplished:

- a. To attain of a reasonably pure hydrogenic plasma at moderate densities and temperatures with stable confinement;
- b. To develop plasma handling techniques, i.e., hardware to initiate, control, and dissipate discharges;
- c. To provide a vacuum chamber of sufficient size, with low base pressure, and equipped for discharge-cleaning; and
- d. To provide a capability for routine pulse operation with reliable gas handling systems.

1.3 Participants in S-1 Design, Construction, and Operation

The primary participants in the design, development, construction, installation, and operation of S-1 are the U.S. Department of Energy (DOE) and the Plasma Physics Laboratory of Princeton University (PPPL).

- a. DOE within its office of Magnetic Fusion Energy has the responsibility for the development of the fusion power program.
- b. PPPL has the responsibility for overall planning, scoping, and monitoring within the guidelines provided by DOE Directives. Ultimate responsibility for the operation rests with PPPL. This includes the operational and environmental health and safety of the operating personnel and the general public. The relationship of PPPL (Princeton University) and DOE is governed by U.S. DOE Contract DE-AC02-76-CH0-3073.

1.4 Summary of Significant Items

The safe design, development, manufacture, fabrication, construction, installation, test, operation, maintenance, modification, and eventual decommissioning is being accomplished in accordance with the safety provisions of the DOE Environmental Safety and Health (ES&H) Orders and the generally applicable environmental guidelines of the Environmental Protection Agency (EPA). In particular, the applicable criteria for routine and accidental occupational exposure to radiation are in accord with DOE Order 5480.1A, Chapter XI⁴ requirements. Applicable sections of the DOE orders have been interpreted and established as design requirements on detailed site related characteristics, buildings and facilities, systems, components, equipment, and operational organization. The site buildings, facilities, and systems have been designed and built to assure safe operation.

A summary tabulation of the principal hazards evaluated and the safety provisions incorporated is presented in Table 1.

2.0 SUMMARY SAFETY ANALYSIS

2.1 Hazards

The operation of this experiment will not generate effluents of any kind which might contribute to the pollution of air or water. Any hazards that accidents may cause are localized, contained, and controlled within the confines of the protective envelope that surrounds the S-1 device and its electrical connections to external power sources.

Specific hazards analyzed were:

A. Materials

1. Toxic or carcinogenic materials are not employed in this operation.

2. Fire hazards

Hydrogen will be used in S-1. The requirements for experiments can be met by using a 30 cu. ft. bottle. The H_2 system will be installed and utilized in accordance with existing standards governing the use and installation of hydrogen.⁵

The explosion hazard from H_2 in this experiment is virtually nil. During experimental operations the hydrogen pressure in the vacuum vessel is less than 0.04 Torr. The worst possible explosion hazard exists if the entire contents of the H_2 bottle would be released within the enclosure. This results in a concentration of one-fortieth that of the lower limit explosive mixture.

B. Electrical Hazards

Large power supplies dominate the operation of the device. All supplies are clearly marked and provided with the necessary interlocks to prevent accidental contact with energized components. All leads are carefully protected against mechanical stress or abrasion.

There are no exposed elements of any energized supply. A master lockout switch is provided to deenergize the appropriate power supplies in an emergency situation. Control computer trip functions, backed up by protective relays, are provided to deenergize the S-1 in case of an abnormality in operation. The Laboratory interlock coordinator has set up a testing program for personnel safety related interlocks.

C. Mechanical Hazards

The vacuum vessel has been designed to conform to the ASME Section VIII⁶ (unfired pressure vessel code) for 1 atmosphere external pressure, gravity, and magnetic forces on the coils. The support structure design conforms to applicable codes and a seismic load of 0.5g. Coils are conservatively designed and will be fully tested before routine operation begins.

Rotating equipment and heavy objects are potential sources of mechanical hazards to personnel.

1. Vacuum pumps - Conventional mechanical vacuum pumps and turbomolecular vacuum pumps are used.
2. Heavy Objects - Many heavy objects will require handling during assembly and maintenance operations. These objects take the form of mechanical equipment, structural members, electrical apparatus, field coils, large electrical bus bars, and similar components.

The risks associated with handling heavy objects will be minimized by following the procedures outlined in the PPPL HSD 5008, Health and Safety Manual⁷ (Section 9.8). The laboratory has a Lift Committee to review other than ordinary lifts.

3. Pressurized Systems - Pressurized systems which present hazards due to the possible creation of projectiles are the following: air receivers, the gas delivery system, and the fire protection systems (Halon 1301).

These systems have been installed as standard acceptable risk systems. The probability of failure is considered to be low and acceptable.

4. Miscellaneous - Portable and non-portable power driven tools such as electric drills and band saws, will be sources of hazard to personnel because of the possibility of improper use or defective equipment.

D. Radiation Hazards

1. Ionizing

Radiation from S-1 is expected to be limited to X-radiation (Bremsstrahlung). The forerunner to the S-1, the proto S-1, did not produce any measurable ionizing radiation. At this time there is no evidence that runaway electrons produce Bremsstrahlung X rays in spheromaks as observed in tokamaks. Monitoring for radiation levels will take a conservative approach as is customary at the start-up of all new devices at PPPL. Thermoluminescent dosimeters (TLD) will be placed on the vessel and the surrounding area to indicate potential exposure dose levels and patterns. Real time high sensitivity monitors will be placed in areas requiring occupancy during initial operations. When new operating parameters are introduced, appropriate surrounding occupied areas will be evacuated until adequate radiation data are collected.

Authorization for operation of new operating parameters of S-1 will not be granted until the Project and Operational Safety Office certifies that there is no radiation hazard.

2. Non-Ionizing

The S-1 will use some lasers for diagnostics. These devices are regulated by HSD 5008,⁷ Section 3. Personnel operating these lasers come under the medical surveillance articles of HSD 5008, which follows ANSI Z136.1-1981.⁸ Because these lasers are interlocked during operations, the potential hazards are related to individuals involved in standard alignment and calibration procedures. These individuals according to Laboratory policy must be knowledgeable in the use of lasers, and, where supervisors request, they will take part in laser training programs.

2.2 Fire Safety

A. Combustible Materials

The Hazards Analysis of the S-1 Project identified the following combustible materials:

1. Hydrogen

It will be used in limited quantities, inventory will be kept small, and when not in use, it will be removed to a secure storage area.

2. Plastic conduits

Plastic conduit is used where electrical noise reduction is required. Plastic conduit is installed in open areas so that any fire would be detected quickly by the fire detection system.

3. Insulating oil.

Oil is used in energy storage capacitors. The energy storage area is enclosed in a two-hour, fire-rated vault, protected by Halon fire suppression. There is a total of five gallons of oil in the MG filter capacitors which are located in an enclosure in the MG area. A metal strip was installed around the perimeter of the enclosure to contain any oil that spills, and a smoke detector that is tied into the PPPL fire alarm system was installed.

4. Wood

Wood with a fire retardant is the principal construction material of the platform. There is adequate fire protection in this area.

5. Control Equipment

Control equipment is protected by a Halon fire suppression system.

6. Contributory Causes

The Accident Analysis identified the contributory causes for starting fire to be primarily electrical faults. Equipment is fitted with safety devices, and protective guards to prevent fire- and operator - personnel injury.

2.3 Property Damage

Fire damage is the principal property damage risk. The facility occupies parts of two floors of a multistory building. The two floors concerned comprise two dual cross zoned areas and contain about 1200 sq. ft. per floor. Both stories are protected by pre-action, dry pipe automatic sprinkler systems. The capacitor-ignitron enclosure and control room are protected by Halon systems. Fire alarm boxes and sprinkler annunciator alarms are connected through the fire alarm system to the fire and security headquarters, which are manned at all times. A trained emergency squad will respond to alarms and backup support is provided by Plainsboro Township.

2.4 Explosion and High Pressure Safety

The Hazard Analysis identified explosion dangers from the following sources:

- A. Electrical Bus Failure. Barriers are installed to contain damage. Bus design incorporates ample safety to prevent dangerous occurrence during normal operation.
- B. Capacitor Explosion. Capacitors are placed in a vault, surrounded by expanded metal mesh to contain any explosion. Circuit protection is installed to prevent excessive energy dissipation inside a capacitor to reduce the probability of a violent event.

- C. Coil Failure. Coils are conservatively designed. The area is surrounded by barriers to contain minor accidents.
- D. High Pressure Airline. A compressed airline enters the area. Pipes are conservatively designed and installation recessed to minimize damaging effects. A protective device cuts off the air on sudden drop in pressure.
- E. High Pressure Waterline. Cooling water is part of the area facilities. Conservative design and sudden pressure drop protection minimizes the damage. Lines are also run recessed to reduce line of sight damage.
- F. Pressurized Gas Bottles. Working gases for the S-1 experiments are contained in standard pressurized gas cylinders. Explosion hazard is minimized by the conservative design of the bottles, by the small inventory of gas, by secure anchoring of the bottles, and by keeping the absolute minimum of bottles in the area.

2.5 Natural Phenomena

2.5.1 Earthquakes

The area is in a low probability earthquake region. All equipment is designed to "most probable" earthquake standards.

2.5.2 Tornados, Extreme Wind

The building was built over 20 years ago. No adverse effect was evident during the most violent winds during this period.

2.5.3 Floods

The area is not in a floodplain and there have not been any floods in its 20 years of existence.

2.6 Noise

There are no significant noise sources associated with the S-1 device or its equipment.

3.0 SITE

3.1 Location

The experimental area for the S-1 Spheromak is the high bay area in the RF building (Fig. 1 and 2), C-Site James Forrestal Campus, of the Princeton University Plasma Physics Laboratory. The area was made available in October, 1980.

4.0 FACILITY AND PROCESS DESCRIPTION

This section contains a summary of a more complete description of the S-1 device as contained in the S-1 Spheromak Project Engineering Handbook, Revision 1, (May, 1981).

4.1 Experimental Area (see Fig. 1 and 2)

The Spheromak experiment utilizes an area approximately 36 ft. by 80 ft. excluding the control room. Some modifications to adjacent areas provided aisles around the experimental area.

A 40' x 30' x 10' high machine platform, convenient for diagnostics, is located around the machine. Extending north from the machine a two story enclosure is provided for capacitor banks and ignitron switches. The capacitor banks, ignitrons, and the machine itself are fenced in. Space has been provided for the future erection of a radiation shield wall if required.

The present RF building has a high bay clear area of 30 ft. by 72 ft. This area is serviced by two cranes: one 5-ton and one 15-ton capacity overhead crane with a hook centerline 28 ft. 6 in. above the floor level. Simultaneous use of the two cranes at full load is prohibited.

The RF building has available the necessary services to provide power and cooling water for the operation of the S-1 machine. The power bus is routed from the MG room to the experimental area passing above the control room and supported from the second floor structural steel (the RF balcony). The bus run is approximately 16 ft. above the floor level and is just to the east of column line #4 which forms the west boundary of the S-1 experimental area. A 6' diameter supply and return manifold from the model C deionized cooling water system is adjacent to the bus run and is adequate for coil cooling requirements. Power for the PF and TF coils will be supplied from the capacitor banks in the S-1 area. The EF coils will be supplied with a 40 kA dc pulse directly from the MG room.

4.2 Power Supplies

4.2.1 General Description

Each capacitor bank (the PF and the TF) has its own dedicated charging supply whose output (up to 20 kV) is connected through high voltage vacuum switches.

The capacitor bank voltage monitoring circuits provide control and display signals. Discharge circuits and grounding switches are parts of each bank. The capacitor banks are connected to their loads through switch modules (ignitrons), coaxial bus work and high voltage coaxial cables.

Control of the electrical system is from the control room. AC single-phase power input to the system controls is filtered to protect the control system from malfunctions due to electrical interferences. Other subsystems have a control and monitor interface with the system controls as well as safety interlocks.

The EF coil system is powered by a pair of existing generators, located in the MG room.

4.2.2 Poloidal Field Power Supply System

The supply consists of a capacitor bank with its charge and discharge circuits. The load consists of six single turn poloidal coils field (PF) embedded in the flux core. It is possible to connect the PF coils in various series/parallel combinations.

The capacitor bank has 40 capacitors of 60 μfd , 20 kV each, capable of storing 480 kJ of energy. The switch connecting the capacitor bank to the PF coils load is made up of eight forward and eight crowbar ignitrons.

The PF current is initiated about 100 microseconds before time zero (i.e., the start of the plasma formation). The PF current builds up to a peak value of about 500 kA at time zero, then rings through zero to a negative maximum of about 390 kA. At this point the crowbar ignitrons are fired and the coil current decays with the L/R time constant of the circuit.

4.2.3 Toroidal Field Power Supply System

The TF bank contains 4800 μfd of capacitance made up of 80 capacitors of 60 μfd each in a parallel arrangement. For normal operation the TF bank can be charged to ≤ 20 kV. The TF bank is discharged into the TF coils through ignitrons. The current is crowbarred at maximum and decays with the L/R time constant. The maximum TF current is about 500 kA.

4.2.4 Equilibrium Field Power Supply System

Two existing model C generators with their associated high-speed resistor breakers and motor-operated safety disconnect switches will be available for the Spheromak device. The generators to be used will normally be #9 and #10 for which there are existing bus pairs already running from the high-speed breakers to the RF high bay area where the S-1 Spheromak is located. Each generator is capable of

being pulsed to 22,300 amperes with an E.S.W. of five seconds once every two minutes. The safety disconnect switches are located just above the high-speed breakers in the MG room. Thus, when the system is disabled, the entire bus run from the MG room to the RF building can be short-circuited and grounded. At the S-1 end of the bus run a switching panel will allow connection of the generators (either in series or parallel) to the Spheromak Equilibrium Field Coil System. Routine control programming in the MG area will allow operation in the series or parallel mode as required by the connections at the end of the bus run. The required 0.1 second flattop current of either 20 kA or 40 kA for the series or parallel circuits is well within the capability of the system.

4.2.5 Switching Modules

The PF and TF switching modules will consist of size 'D' ignitrons. Each of these tubes is rated to hold off 25 kV, carry a peak current of 300 kA, and conduct 200C once a minute.

The parasitic inductances are low compared to coil inductances and high enough to limit the fault currents.

The number of parallel ignitrons was chosen to conduct the worst case peak current and the worst case of charge without permanent damage.

4.2.6 PF/TF Electrical Bus

Coaxial buses interconnect the capacitors within each bank and collector plates provide a termination for connection of the charging supply (for each capacitor bank) and for connection of the bank output to its switch module. All bus work is mechanically braced for maximum possible fault currents, insulated for high voltage, and adequately sized for natural cooling during normal duty cycle operation. It is configured for low self inductance and minimum ground current.

High voltage cable is provided from each charging supply to the capacitor bank, and multiple coaxial cables from the switch module output terminals to the machine coils. Grounding and disconnect switches are handled as high voltage devices.

At the machine end, the coaxial cables are terminated on collector plates similar to the ones used at the switch modules.

4.2.7 Charging Supplies

The charging supplies charge the PF and TF capacitor banks at a rate consistent with the duty cycle of the machine. The input to these charging supplies is 480 VAC, 3 phase.

Voltage control is provided in the system so that capacitor bank voltage may be varied from approximately 4 kV to 20 kV. Control of this voltage is accomplished from the control room. The charging supplies will be completely disconnected from the capacitor banks by vacuum switches before the banks are discharged into their loads.

The voltage level of the capacitor banks will be monitored and a voltage level signal is provided through safety breaks to the central control room for display and control of the capacitor bank voltage level.

A discharge and grounding circuit (at the terminals of each capacitor bank) safely discharges each bank and grounds the bank output when the system is not in use. The operation of the switches in the grounding circuit is visible from a safe area that permits observation of their position. The positions of the grounding switches can be monitored by the control system. The charging supplies are inhibited as long as these switches are closed.

Safety interlocking is provided so that personnel do not enter the area of the capacitor banks and charging supplies unless the banks are connected to their discharge circuits and their outputs grounded. Access to capacitor bank areas is in accord with HSD 5008, Section 2. Keys for the area are in the custody of the Head, Engineering Services Group.

4.3 S-1 Device

A cutaway view of the S-1 device is shown in Fig. 3.

4.3.1 Coil Systems

A. Flux Core

The geometry of the core is a torus which contains three separate windings. The flux core has a major radius of 1 m and

a minor radius of 19 cm. Figure 4 shows a cross section of the flux core. It contains:

1. A 90 turn toroidal field (TF) winding, divided into six 15 turn sections, capable of operating at levels up to 7.5 MAT. Table 2 gives the main parameters of the TF winding.
2. Six one turn poloidal field (PF) winding capable of operating at levels up to 0.5 MAT. Table 3 gives the main parameters of the PF winding.
3. A two turn equilibrium field (EF) winding capable of operating at levels up to 80 kAt.
4. An aluminum shell over all three windings broken in both the poloidal and toroidal direction to act as a passive stabilizer and to reduce the TF ripple.

Figure 5 shows a schematic view of the windings inside the flux core.

B. Liner

The entire core is enclosed in a thin Inconel liner (0.010").

The core has radial arms, seven of which provide conduits for electrical connections to the various windings. The other three support the core in the vacuum vessel.

C. EF Coil System

The Equilibrium Field Coil System provides a vertical field with curvature that can be varied to provide equilibrium by restraining the tendency of the toroidal plasma current to expand. It also determines the shape of the plasma according to the curvature of the equilibrium field.

D. MG Filter

In Mode A, B, or C operations there is significant coupling of the PF circuit with the EF circuit because in these modes the EF-4 coil, which is located inside the flux core, is connected. For this reason, a filter circuit is included in the EF circuit, as shown in Fig. 12, to limit the induced current that flows in the MG sets.

The MG filter coils and the MG filter capacitors are located in two separate enclosures in the MG area (see Fig. 13). The doors of the MG filter coil and capacitor enclosure are secured with the locks being controlled by Kirk Keys which are a part of the S-1 Kirk Key interlock system.

4.3.2 Vacuum System

A. Vacuum Vessel

The vacuum vessel is composed of three basic segments. The north and south domes are 126-inch diameter flanged, dished heads (100.8 inch radius) and a 1/2" thickness. Between these is a flanged, central rolled cylinder of 63-inch radius and 1/2"

thickness. The central rolled cylinder is a part of a sub-assembly which includes the flux core mounted in it. Having the chamber separable into three major parts simplifies maintenance and modifications.

The vacuum chamber serves a dual purpose by providing the basis for the EF coil support system. Welded onto the north-south domes are eight radial 1/2" thick ribs which form the structural system for the support of the external EF coils. At each of these eight toroidal locations three pairs of pads are provided for the EF coils. These pads locate and anchor the coils in the radial and Z directions. Clamping plates then are used to hold each of the coils in a fixed position.

The EF coil rib support system results in a natural segmentation of the vacuum vessel domes into eight pie-shaped segments. Each of these segments contains large ports, arranged on a constant circumferential line. Additional ports are located equatorially on the central rolled segment for lead penetration and additional diagnostic access. Two large ports at the north-south end of the machine are arranged co-axially on the horizontal midplane.

B. Vacuum Pumping System

The pumping system consists of two identical pumping stacks in parallel, each using a turbomolecular pump backed by a blower-mechanical pump combination. Two separate pumping stacks will

allow independent operation in the event of equipment failure in a single pumping stack.

The required time to pump the system down from atmospheric pressure to 10^{-6} Torr is estimated to be approximately 30 minutes. The effective pumping speed from each pump system is 1000 liters per second.

C. Support Structure

The basic function of the S-1 structure is to support the device in the position shown in Fig. 2. The vertical orientation facilitates access to ports on either dome. Diagnostic devices lie in the horizontal plane. The height above the floor line was set to allow passage and access from below the machine.

The machine substructure is a 4-legged rigid frame aluminum weldment anchored to the concrete floor. The north dome is supported on a 2-pedestal bridge structure of welded stainless steel that is bolted to the substructure. Two radial I-beam support legs welded to the dome attach the dome to the pedestal bridge. The south dome is mounted on support legs welded to the dome (similar to the north dome). The south dome support legs are mounted on a carriage that permits 34" of horizontal north-south translation when the south dome is detached from the north dome and center section. The carriage supports the south dome when it is freestanding.

The support frame has insulating breaks to eliminate induced loop currents. The vacuum vessel is supported from the framework on insulating pads that provide electrical isolation.

4.4 S-1 Operating Controls

4.4.1 Introduction

The S-1 Spheromak will require the coordinated operation of six subsystems. These are:

- EF coil system
- PF coil system
- TF coil system
- Water cooling system
- Vacuum and gas system
- Safety system.

The S-1 operating controls utilize an LSI-11/23 processor and a CAMAC system. There are four CAMAC crates in this system, and it can easily accomodate future growth. Figure 6 shows the physical arrangement of the crates and the distribution of control/monitoring tasks among them. The PF/TF and MG crates handle functions that deal with the specific subsystems. The machine area crate is used for a variety of subsystems. The module arrangement in these crates is shown in Figs. 7 and 8.

The vacuum system will have its own dedicated controller. Provisions will be made to interface with CAMAC, but this interface, at least initially, will be limited to remote monitoring.

The safety system (see Section 4.4.2) is hardwired but linked to the computer for annunciation.

The CAMAC crates are connected together in a loop by fiber optic cables, which in conjunction with a serial highway driver module, three serial crate controller modules, and U-port adapters, forms the serial highway. Locating the crates close to the control interfaces reduces cabling requirements significantly. The fiber optic cables satisfy electrical safety requirements, and eliminate electromagnetic interference problems along this communication link.

The timing signals for event controlling are generated by a timer system composed of distributed TFTR CAMAC timing modules. The encoded clock signal, which is transmitted on a fiber optic link, interconnects all the crates in the system.

All remote crates contain a watchdog timer module. If not updated within a preset period of time, all power from the CAMAC output contacts will be removed, causing equipment shutdown.

4.4.2 S-1 Safety System

The machine area is accessed by four entrances. Each of these doors will be provided with the following devices (see Fig. 9):

- A. Kirk Key controlled lock (SK),
- B. Electric door interlock (DI),
- C. Emergency shutdown station (ES),
- D. Kick-out panel.

In addition there are two double doors on the east wall which are permanently closed and are provided with electrical door interlocks (DI).

The MG area contains a capacitor and inductive enclosure with access doors that are provided with a Kirk Key controlled lock (SK), and electrical door interlocks.

An emergency shutdown station (ES) is conveniently located on the MG area capacitor enclosure wall.

The EF Mode switch panel enclosure located on the first floor beneath the S-1 vessel, and the MG switch panel enclosure located in the MG area, are both padlocked. The keys for these padlocks are in the possession of the MG Control Engineer so that changes in EF Mode without consulting the MG Control Engineer are prevented.

The Kirk key diagram is shown on Figs. 9 and 10.

The safety lockout switch (referred to at PPPL as a "Grove" switch) is the heart of the system (Figure 11). It provides access to the master key when the drum is turned to the safe position. This can only be performed when all power supplies are disabled, disconnected, and the coils are grounded. In this position all disconnect switch control power is removed by a contact on the safety lockout switch. The circuit to energize the shorting/grounding switch "open" solenoids is also disabled. The power supply switch is a manually

operated safety switch keyed to the "Grove" switch. The grounding switch positions are viewed through a window at which a key is located for use at the "Grove" switch.

4.4.3 Emergency Shutdown

Emergency shutdown stations are accessible from both inside and outside of each doorway, in the MG area on the capacitor enclosure wall, on the first and second floors inside the machine area, and on the control console in the control room. Each consists of a red mushroom button with a reset button below it. Each station is identified by a red indicating lamp and a sign. A hard-wired series circuit with normally closed contacts maintains a relay energized under normal conditions. Operation of any shutdown station causes an immediate shutdown of all systems, including the water system. Every station is monitored by the CAMAC system to provide detailed annunciation. Loss of power to the hard-wired control circuits will cause an emergency shutdown.

All electric door interlocks and key switches are monitored by CAMAC.

No subsystem may be energized unless the emergency shutdown system is in the reset (normal) mode, all door interlocks indicate doors closed, and the safety lockout switch is in the unsafe position.

4.4.4 EF Control System

A. System Configuration

The EF (Equilibrium Field) coils on S-1 are powered by a pair of 600 volt "Model C" motor-flywheel-driven DC generators, (Fig. 12), each of which is capable of driving a maximum current pulse in excess of 20 kA. Several electrical interlock contacts must be transmitted both ways between S-1 operating controls and the generator control center (MG control room), following a standard protocol used for various experiments since the C-Stellarator. Safety grounding and disconnect switches as well as resistor and high speed breakers must be operated by S-1 controls.

Cooling water flow paths are monitored for EF coils and water-cooled buswork; acceptable flows and water temperatures in these paths are required for EF operation. S-1 controls will also verify that flow sensors indicate no flow when water is off.

S-1 operating controls produce a timed analog current reference signal pulse proportional to the desired EF current, as a command input to the generator control systems.

The EF coil system includes seven coils, four of which have single internal electrical taps, and two have double internal taps. A patch panel with removable bus links will allow these coils to be connected in any of four desired configurations, using various series and parallel coil connections. A second patch panel allows the generators to be connected in either

series or parallel. All potential bus link positions on the panels contain limit switches that are monitored by the S-1 operating controls to verify that the circuit is correctly connected before permitting operation.

The S-1 operating controls monitor actual EF currents via two resistive "shunts," located in the EF patch panel. These currents are monitored for proper operating levels. Also the control computer calculates the temperature rise of the EF-4 coil by real-time numerical integration and ensures that it is within safe limits. This is used to abort EF operation, if necessary. As a backup to this protection a transducer with two associated time over current relays performs I^2t integration and also causes an independent trip. Additionally, EF operation is shut down if commanded current is not sensed to develop, because that could signify a sensor failure.

The EF control system can be represented by the block diagram shown on Fig. 14. The control and status signals and current monitoring information are transmitted on the CAMAC serial highway between the central control computer and appropriate CAMAC modules. In addition there are two additional cables that link the control room and the MG controls: one for the transmission of the encoded 1 MHz clock signal for accurate timing commands, and an emergency shutdown line which connects the machine area shutdown buttons. There is an independent I^2t disable line which disables the generators when the EF timed over current relay trips.

B. System Operation (Fig. 15)

The control of the generators follows the standard protocol which is used for all experiments. For the purpose of this discussion the following functions were defined:

SHUTDOWN:

This function disables the EF circuit, and trips the generator field circuits.

DISABLE:

This function disarms the EF circuit, trips the generator high-speed breakers, after a time delay opens the resistor breakers, and after another time delay opens the disconnect switches.

ENABLE IN OPERATE MODE:

This function closes the disconnect switches, then the resistor breakers, and finally the high-speed breakers.

ENABLE IN CHECK MODE:

This function closes the disconnect switches only, permitting manual closing of generator breakers by MG.

DISARM:

This function disconnects and shorts out the reference signal path to the generator comparator.

ARM:

This function closes a permissive contact in the reference signal path to the generator field controls.

In order to operate the disconnects and the generator breakers totally from the S-1 control room both MG and S-1 controls must be set to OPERATE mode. This can be done either in the fully enabled state or in the disabled state. (Note: Normal start-up procedure requires the first enable to be performed in the check mode. After the breakers are closed by MG operators, the control is then transferred to S-1.)

In the OPERATE MODE the enable command causes the disconnect switch to close and to be followed by the automatic closure of the generator breakers.

When ENABLED in OPERATE MODE, the system can be ARMED and subsequently pulsed into the EF load.

In any of the states either the operator or the computerized control system can command DISARM or DISABLE.

4.4.5 PF/TF Control System

A. Introduction

The PF (Poloidal Field) and TF (Toroidal Field) power supplies are nearly identical (Fig. 16), consequently the control system is essentially identical for both. The control of these power

supplies is provided solely by the S-1 control room. These coil systems do not employ load disconnect switches. Instead, grounding/shorting switches will be used on each capacitor bank. The switches are solenoid activated and will be mechanically latched open, so that momentary loss of power will not short-circuit the capacitors.

Power for each coil system is supplied by independent capacitor banks. The capacitor bank voltages are controlled from the S-1 control room and can be changed to a maximum of 20 kV. At selected times the PF and TF "forward" ignitrons will be fired, connecting the capacitor banks across their respective coil systems. The resulting PF and TF currents are each damped sinusoids, both with periods of 400-2400 microseconds with maximum peaks of about 500 kA. Each current waveform will be modified at a preselected time during its first cycle, when banks of PF or TF "crowbar" ignitrons are fired, shorting together the PF or TF coil system terminals. Subsequently, the current decreases according to the L/R characteristics of each coil system.

B. System Configuration

The PF/TF control system can be represented by the block diagram in Fig. 17. The control and monitoring of the PF/TF power supplies and loads will be done via the CAMAC serial highway.

The machine area crate senses the PF/TF flow status, and the ground fault detector signal. Twelve current transformers measure the PF and TF coil currents. Transient digitizers record the waveforms and store them temporarily in their associated memory modules. These waveforms can be retrieved after the shot and displayed on storage scopes. At the present, no additional modules are provided for voltage measurement. If necessary, the same digitizers could be shared.

C. System Operation (Fig. 18)

In order to facilitate the description of the operating sequences the following functions were defined:

DISABLE:

This function disarms the PF/TF circuit, trips the main contactor, and after the capacitors have discharged closes the shorting/grounding switches.

ENABLE:

This function opens the shorting/grounding switches, and closes the main contactor.

DISARM:

This function opens the charging vacuum switches, turns off the solid state contactor, and closes the discharge vacuum switches.

ARM:

This function provides the permissive contact for the capacitor charge/discharge cycle.

START CHARGING:

This function initiates the charging of the capacitor banks, by opening the discharge vacuum switches, closing the charging vacuum switches, and turning on the solid state contactor.

In any of the states either the operator or the computerized control system can command DISARM or DISABLE. The grounding switches will only be closed after the capacitors have been properly discharged.

4.4.6 Vacuum System

The S-1 vacuum system (Fig. 19) is expected to be operated continuously and unattended for long periods between S-1 experimental periods as well as during the experiments. Its interlocks are thus implemented in a self-contained local controller. Two modified "TFTR diagnostic vacuum controllers" are used. All pump and valve sequencing, protection features, as well as interfacing to CAMAC will be implemented by these controllers. The CAMAC interface contains features for remote controlling of the vacuum system; however, initial operation will provide status monitoring only.

The S-1 vacuum system includes two identical vacuum pumping lines. Each line contains a chain of three pumps (a mechanical pump, a roots

blower, and a turbomolecular pump); four electro-pneumatic valves (a high-vacuum valve, a roughing valve, a foreline valve, and a vent valve); three thermocouple pressure gauges; and one ion pressure gauge. The mechanical pump reduces the pressure from atmospheric (760 Torr) to several Torr; the roots blower pump reduces the pressure further to about 10^{-3} Torr, and the turbomolecular pump reduces the pressure the rest of the way to about 10^{-6} Torr.

The following controls and interlocks will be implemented:

- The mechanical pump is normally controlled on/off with no interlocks except for internal overload protective functions.
- The roots blower is energized automatically through its controller, whenever the mechanical pump is on and the foreline and torus pressures are below adjustable setpoints (several Torr). It is deenergized whenever any of the three above conditions are not satisfied.
- The roughing valve is only opened and closed under manual control. However manual opening is inhibited when either the foreline or the high vacuum valve is open.
- The foreline valve is opened under manual control subject to the condition that both the roughing valve and the venting valve must be closed. It is closed automatically whenever the foreline pressure is above a set point, or before opening the vent valve.

- The turbomolecular pump is only started by manual control, provided the cooling water flow is satisfactory. It can be turned off manually, and will be turned off automatically if cooling water, or other internally sensed problems develop. It will also be turned off if the exhaust pressure is above a set point.
- The high vacuum valve is only opened by manual control. The permissive conditions are that both roughing and venting valves must be closed, S-1 pressure must be below a setpoint, and the turbo-pump must be running.
- The vent valve is automatically opened after the turbopower has been off for an adjustable period. Prior to opening the vent valve the foreline valve is closed.

4.4.7 S-1 Water Control and Monitoring

A. Water Control

Two valve actuators with single phase reversible motors are used. These are wired for sequential operation, i.e., at start-up the return valve must be open before the supply valve opens, and at shutdown the supply valve closes before the return valve. This operation is controlled and monitored by CAMAC. Turning the water system on or off is initiated by operator command, coordinated by MG control. Before executing the "on" command, the control system checks all flow switches for "stuck" mode failure (Fig. 20).

B. Water Monitoring

Thirty-one normally open flow switches and 31 normally closed temperature switches monitor the coil cooling water. Nine additional flow switches are used on ignitron cooling water paths. These contacts are wired into CAMAC modules. As a prerequisite to enabling any of the power supplies, all flow and temperature switches must be closed. During operation any switch opening will disarm all coil power systems. The systems may then be disabled by operator command if necessary.

4.4.8 S-1 Computer and Man-Machine Interface

A. Computer System

The S-1 computer system resides in the S-1 Control Room CAMAC crate. It consists of a direct memory access (DMA) crate controller (KS-3923), which provides the complete interface between the LSI 11 computer (KS-3823) and CAMAC. A real time clock interrupt required by DEC software for event synchronization and time-of-day functions is also generated.

B. Man-Machine Interface

The man-machine interface allows complete control of all S-1 parameters required for machine operation. The primary controller is a 16 button touch panel display CRT. Separate displays for PF/TF, EF, safety, water, and vacuum systems are automatically presented to the operator, or are callable by operator command. Simulated buttons will have functional labels

and will flash on-off for increased operator attention. Along with this CRT, mimic panels for each of the above indicate the state of the subsystems at all times. Secondary operator input is from the system console, where timer channel settings and other system parameters are entered. The computer operating system, however, is locked out during machine operation.

C. Timer

To accomplish synchronous control throughout the S-1 control system a timing system, consisting of TFTR modules, is used. The main components of this system are:

1. Clock generator module;
2. Clock encoder module 401-2;
3. Timing module 404;
4. Digital timed gate 305.

The timing signal characteristic of this system is accomplished by distributing an encoded clock signal to the timing modules and digital timed gates. In normal operation, these receiving modules monitor the encoded clock signal, and perform a specific action upon recognition of a particular code. Specifically, the timing modules start a time delay whose length is programmable by CAMAC commands (from 1 microsecond up to 16 minutes), and output a 5 V, 1 microsecond timing pulse. The digital timed gate uses the clock signal for time synchronization only. It does not make use of the encoded information. The digital time

gate is triggered by pulses generated by timing modules, or alternatively by CAMAC dataway commands. Upon receiving a trigger the digital timed gate turns on its output and remains on for a predetermined period. The period may be programmed from 1 microsecond to over 17 minutes.

4.4.9 Grounding

A. Introduction

Grounding has to satisfy a number of considerations.

1. Minimize Interference

The magnitude of the ground current must be kept to a minimum, and its spread along spurious grounds should be restricted. To this end the basic approaches are:

- a. symmetrical capacitance distribution;
- b. single point ground;
- c. avoid loops;
- d. low inductance ground connection.

2. Provide Safety

Personnel as well as equipment safety depends on minimizing voltages that appear at nearby points, i.e., adjacent to each other or at space occupied by personnel.

3. Provide return for power short circuits. This is required by the National Electric Code. It is also common sense not to let the short-circuit current of the AC power spread

along the grounding grid. Equipment grounding conductors run with or enclose the circuit conductors (NEC).

4. The layout of the grounding grid does not lend itself to pick up induced voltages from the stray flux of the experimental machine.

5. Steps taken for S-1:

- a. Ground currents will be minimized by symmetrical stray capacitance distribution.
- b. Single point ground will be enforced.
- c. The National Electric Code will be observed.
- d. Simple monitoring will be instituted that will sound an alarm if accidental violation of rule b. appears.

B. Spheromak Ground

The Spheromak machine inherited a building ground grid from the C-Stellarator installation.

The single "ground point" is a geometrical point at the Spheromak. This will be connected to building ground with insulated MCM cable.

C. Control Room Ground

The Control Room is enclosed in a metallic shield (screen) that is insulated from the surrounding grounds.

Equipment located in the control room will be connected to the control room ground with short straps. The control room ground is connected to a driven ground with insulated #2AWG conductor. Grounds on power and signal cables should have an insulating break as they enter or exit. Inside the control room cables will be run in overhead trays. The tray will be routed to avoid loops.

D. AC Power Ground

The AC power is supplied through a number of high dielectric isolating transformers to the following loads:

1. Capacitor charging supply.
2. Control room power and light (The low voltage side is filtered).
3. Power for diagnostics and CAMAC crates (on machine platform).
4. Power for vacuum system and water system plus certain light fixtures. These will be fed from the diesel powered bus so that in case of power outages these still function.
5. Heat lamps for ignitrons, outlets for the energy storage area, power for cooling fan.
6. Welding outlets, lights, and convenience outlets for the experimental area.

These transformers are located so that the supply network is radial (does not form loops).

All enclosures are connected to the local ground. In addition, the primary ground of the supply transformers is brought to this point in bare ground wires and in metal conduits.

The secondary circuits of the transformers (including any neutrals) (entering areas of different ground planes) are designed to be isolated from nonhazardous power supply sources. If enclosed in metal conduits, the conduits have an insulated segment which forms an isolation break between different ground areas. Secondary side neutrals are connected to the Spheromak ground.

E. Fence Ground

The external fence is connected to a nearby building ground.

F. Conduit Ground

In order to limit ground loops, a single point ground system has been adopted for S-1 as noted in Secs. 4.4.9.A.1 and 4.4.9.A.5. This means that different elements of S-1 are electrically isolated from each other except for an insulated ground cable which is connected to the single point ground. Metallic conduits are grounded to nearby elements. If a conduit extends from one isolated area to a second isolated area, it then has an insulating break.

Metallic conduits are connected to the local ground. If the conduit enters an isolated ground plane area, it will have an isolation break.

The conduits (rigid or flexible) leading into the energy storage or experimental area are:

1. short.
2. radially arranged (i.e., emanating from a single ground).
3. grounded at only one point and mounted on insulating support along the run.
4. electrically continuous except when entering different ground areas.

G. Cable Tray Ground

Cable trays, like conduit, are grounded.

In any case they are:

1. Properly separated considering voltage level, noise, etc.
2. Supported or suspended with intervening insulating elements.
3. Carrying grounding cables or strips.
4. Electrically continuous, i.e., splices should be bonded, except as they enter different grounding areas where insulating breaks are used.

H. Instrumentation Leads, Interlock and Control Cables, Monitoring Connections

Signal leads from instrumentation and diagnostic devices will be carried through shielded twisted pair cables.

The shields of coaxial cables are grounded only at one end.

These leads will be routed in covered cable trays or conduits.

Optical fibers are installed in raceways along with instrumentation cables, but are clearly marked or separated. Care must be taken to mark the optical fibers clearly because they can break if bent.

The general rules follow:

1. The wires are regarded as high voltage wires.
2. Coaxial or shielded cables are used with shields grounded at one point only.
3. The cables are routed in trays that radially emerge from the Spheromak.
4. The wires and contacts (door interlock, flow switch, actuator coil, crane interlock) are insulated from the local ground.
5. Connection from different ground areas to the CAMAC crates should be carried through insulating breaks. (Light insulators or vacuum relays).

I. Structure Ground

The Spheromak machine structure is grounded to the single machine ground. Capacitor racks are made of fiberglass.

Metallic structures near S-1 will be

1. Projecting radially outward from the single ground,
2. Grounded at one point only.
3. Configured to avoid creating loops, and
4. Segmented.

J. Water Connection Ground

The water connection will have an insulating break as it enters different ground areas. Entry is planned for the Spheromak machine through a manifold, and the ignitron area through an insulating hose.

Care must be taken to avoid loops.

The water pipes at the Spheromak machine will be grounded at one point to the machine ground. The piping otherwise will rest on insulating supports.

The water pipes at the ignitron area will be grounded to a local ground and will rest on insulating supports.

K. Halon Piping and Halon Control Ground

The Halon tank and piping are on one elevation (one plane), supported on insulators, grounded at one point through insulated cable, and do not form a loop. The control panel and Halon tank are grounded at the local ground; and joints in piping are bridged with a conductive strap, except when they pass through different ground areas.

L. Sprinkler System

Water piping for the sprinkler system is subject to the same rules as cooling water connections. In addition the layout follows the piping philosophy of the Halon system.

M. MG Filter Ground

The MG filter is ungrounded except through the MG ground. Any instrumentation control, or interlock should be grounded at one point.

N. MG Control Cable

The MG control is presumed to carry the fault current on its integral grounding conductors. Thus its display, instrumentation, etc. in the control room are handled as high voltage equipment. Required personnel protection is achieved by using visual contact only, i.e., out of reach (behind barriers), and any settings or parts that require manual communication are optically isolated.

O. Energy Storage Enclosure Fan

A fan with proper ducts provides cooling for the energy storage vault. It is interlocked with the fire protection system. In case of a fire the fan stops and the wall louvers are closed.

P. Vacuum Ground

The vacuum vessel is connected to the machine ground through an insulated cable. There is an insulating break in the vacuum line and beyond the break the ground is building ground.

The vacuum control cabinet is grounded through an insulated cable to the local ground. The power cables to the power panel are run in conduit, and the vacuum control cabinet is in the machine area.

Q. Water System Power

Considerations are similar to those of the vacuum system.

R. Temporary Grounds

In course of operation and experimentation, temporary grounds are required to discharge the capacitors before touching, to set up new instrumentation, or to observe experiments at close range.

For temporary grounds, bolted connections will be provided to local ground plane at various points. The experimenter will be able to bolt a ground to these positions.

S. Electrostatic Shield (Screen)

The control room is within an electrostatic shield box consisting of:

1. Sandwich panels of insulating material and metal screen from the walls and ceiling of the room,
2. Metal covered doors with straps and contact fingers to assure electrical continuity,
3. A wire mesh over the openings with straps connecting to the rest of the shield, and
4. Grounds at two places to a driven ground. (The measured resistance to ground is 32 ohms.)

T. Expanded Metal Frame Around the Capacitor-Ignitron Vault

The expanded metal screen is connected to the Spheromak ground.

U. Air Conditioning Ducts

The energy storage area needs ventilation. This will be accomplished by a fan that sucks in air from the first floor of the machine area and exhausts outside the area.

The control room requires an air conditioning system to maintain a controlled environment for the control system computer. Without this system the temperature would be excessive due to the electronic equipment used for physics instrumentation.

The supply and exhaust for the air conditioning system are located outside the electrostatic shield of the control room.

4.5 Fire Protection

4.5.1 Fire Protection System

Fire damage is the principal property damage risk. The facility occupies parts of two floors of a multistory building. The two floors concerned comprise two dual cross zoned areas and contain about 1200 sq. ft. per floor. Both stories are protected by pre-action, dry pipe automatic sprinkler systems with the second floor region designed for ordinary hazard occupancy. Fire alarm boxes and sprinkler annunciator alarms are connected through the fire alarm system to the fire and security headquarters which are manned at all times.

All fire alarms are also monitored by the plant monitoring system that provides information in a matter of seconds on the exact location of an alarm and on planned procedures. The system is computerized and includes the fire alarm boxes and sprinkler annunciator alarms for all PPPL occupied buildings. A Halon fire protection system is installed in the energy storage vault adjacent to the machine area. Smoke detectors that are located in the energy storage enclosure initiate the Halon release sequence, close the vents in the energy storage area, and shut off the ventilation fan.

The control room is protected by a Halon system. When the control room smoke detectors are triggered, dampers in the air conditioning ducts are automatically closed.

4.5.2 Fire Fighting Personnel and Equipment

The Plant Emergency Squad, consisting of 25 people, responds to all alarms with a pumper, a fully equipped emergency truck, and an ambulance, according to need. At least five full time fire fighters are available for each shift, 24 hours per day, seven days per week. (Another pumper and a CO₂ truck serve as backup.) Under mutual aid agreements additional personnel and equipment from other plants and Plainsboro Township will respond and provide backup in the event of larger emergencies.

Activation of the sprinkler system will deenergize power supplies for S-1. Any new power supplies that present an additional fire hazard will be installed in conformance with existing strict fire protection codes governing the building in which this experiment is housed. The capacitor-ignitron enclosure as well as the control room have Halon protection.

5.0 HAZARD ANALYSIS

5.1 Accident Analysis

Tables 5 and 6 note the accident detection, effects, and corrective actions for components of the S-1 that could be involved in an accident.

5.2 Failure Mode Analysis

Tables 7-18 note components and modes considered in a failure mode analysis along with the potential effects and corrective actions.

6.0 QUALITY ASSURANCE

During the design, fabrication, construction, and operational phases of S-1, the background quality assurance program at PPPL has been evolving from one of project level policy/procedure to one where laboratory-wide Quality Assurance top level policies limit the extent of project differences in applying appropriate design, process, and operational controls. The assurance disciplines currently imposed during S-1 operation and during planned or unplanned maintenance shutdown and start-up are identified in detail in PPL-QA-002, Quality Assurance Program Plan (in preparation) and Supporting Procedures.

Table 19 shows the assurance controls currently exercised during the operational phase of S-1. Again, this table is limited to elements of S-1 that are required for safety, i.e., those subsystems, components, and procedures directly related to preventing the exposure of personnel to hazardous conditions or the accidental release of stored energy.

7.0 CONDUCT OF OPERATION

7.1 Organization

The Laboratory has compiled a set of Health and Safety Directives (HSD's) which describe safety organization and responsibilities.⁹ Safety at PPPL is considered to be a line responsibility¹⁰ extending throughout the line organization to all Laboratory employees. The Project and Operational Safety Office maintains a close liaison with the S-1 staff to provide input at all S-1 operational meetings. A project safety coordinator has been assigned to provide a single point of contact between the P&OS and S-1 organizations. In addition, the PPPL Occupational Medicine and Safety Branch provides an independent audit function of safety processes.¹¹ Also area safety coordinators are assigned to all areas of the Laboratory in accordance with HSD-5002.⁹

7.2 Training

Training is addressed in HSD-5028.¹² In addition the Laboratory is preparing a comprehensive training program.

All devices at PPPL including S-1 require skilled and well-trained employees. Specifically, in the area of safety training, sessions have been held on fire protection systems, including Halon. All training will meet the requirements and standards of the Laboratory. The S-1 project managers will be responsible for identifying employee deficiencies and ensuring their enrollment in required courses.

7.3 Testing Program

Preoperation and operational testing is conducted on all new equipment, components, or structures. Written procedures are used for new tests and are signed off by P&OS. New operating parameters which have a potential for radiation production are monitored by P&OS and subsequently released for routine operation by written memo.

7.4 Configuration Control

No formal configuration control board has been set up for S-1. However, S-1 personnel understand the necessity for "as built" drawings and current electrical schematics. Laboratory policy will dictate the requirements in this area. SOP-2, which is the procedure for implementing QA Directive 001, will be generated.

7.5 Procedures

HSD-5015¹³ encourages written procedures for most operations and requires them for unusual hazards. The S-1 project uses written procedures in accordance with this HSD.

7.6 Safety Review System

An independent safety review is provided by HSD-5024.¹¹ New systems and procedures will have safety review and signoff. In addition, area safety coordinators will note deficiencies on a daily basis and management will schedule safety walk-throughs of the area.

7.7 Emergency Planning

Emergency plans follow the requirements of HSD-5007.¹⁴ This is a Laboratory wide plan which addresses emergencies site-wide, and defines responsible individuals, training programs, and emergency drills and exercises.

8.0 ACKNOWLEDGMENTS

Many PPPL individuals have been involved to date in the installation, safety assessments, and operation of S-1. These individuals include, but are not limited to, J. Joyce, D. Mullaney, F. Dahlgren, G. Oliario, F. Lawn, R. Helmich, J. Chrzanowski, W. Heim, A. Janos, and M. Yamada. G. Bonner must be singled out for his efforts in the original collection of information for this document. Safety office reviews by F. Beane, R. Jeanes, P. Del Gandio, and C. McBride are acknowledged. C. McBride must be singled out for his diligence in insuring a safe start-up. Also J. Ives and J. Fennimore have worked on providing the proper start-up radiation monitoring. This document has had a broad review within the PPPL community to assure the safe operation of this low hazards device. The reviews have included safety, emergency services, quality assurance, engineering, management, and operation personnel.

9.0

REFERENCES

- 1 PPPL Health and Safety Directives, (HSD)-5003, Operation Hazards Criteria, 7/28/82 (unpublished).
- 2 Safety Analysis and Review System, DOE Order 5481.1A, U.S. Department of Energy, Washington, D.C., 8/13/81.
- 3 Safety Analysis and Review System (SARS), DOE/Ch Order 5481.1A, U.S. Department of Energy, Chicago Operations Office, 3/26/82.
- 4 Operational and Environmental Safety Division, Environmental Protection, Safety, and Health Protection Program for DOE Operations, DOE Order 5480.1, Chapter XI, U.S. Department of Energy, Washington, D.C. 8/13/81.
- 5 NFPA 50A-1978, Standard for Gaseous Hydrogen Systems at Consumer Sites.
- 6 ASME Pressure Vessel Code, Section VII, Unfired Pressure Vessels.
- 7 PPPL Health and Safety Directive (HSD)-5008, Health and Safety Manual.
- 8 American National Standard Institute (ANSI) Z136.1-1981, Laser Safety.

- 9 PPPL Health and Safety Directive (HSD-5002), Organization, 7/28/82 (unpublished).
- 10 PPPL Health and Safety Directive (HSD)-5001, Safety Policy, 7/28/82 (unpublished).
- 11 PPPL Health and Safety Directive (HSD)-5024 Independent Review, 2/01/83 (unpublished).
- 12 PPPL Health and Safety Directive (HSD-5028) Training, 12/6/82 (unpublished).
- 13 PPPL Health and Safety Directive (HSD)-5015. Written Operating Procedures, 12/6/82 (unpublished).
- 14 PPPL Health and Safety Directive (HSD)-5007 Emergency Preparedness Plan, 10/82 (unpublished).

T A B L E S

A N D

F I G U R E S

TABLE 1. HAZARD EVALUATION AND DESIGN PROVISIONS

Consideration	Provision
Hydrogen	<p>Installation per established safety codes.</p> <p>Air/H₂ mixture concentrations safe for all failure modes.</p>
High voltage	<p>Interlocks, locks, fences, ground provisions, insulation, marking, controls.</p> <p>All interlocks identified in operations procedure and verified prior to facility operation, tested periodically.</p>
Radiation	<p>X rays only potential problem; safety office issues authorization for safe operation.</p> <p>Continued monitoring as experiment progresses.</p>
Coils and mechanical equipment	<p>Design margins adequate for stress and deflections.</p> <p>Design margins verified by tests.</p>
Fire enclosure	<p>Enclosure is within a building protected by automatic sprinkler system.</p> <p>Capacitor-Ignitron enclosure and control room will have additional Halon system.</p> <p>Building materials and construction are in accordance with fire protection codes.</p>
Power supplies	<p>Installed per fire protection codes and N.E.C.</p>

TABLE 2
TOROIDAL FIELD WINDING PARAMETERS

Major Radius:	1 m
Minor Radius:	15 cm
Total Turns:	90, arranged in 6 groups of 15 connected in parallel
Max Current:	83.3 kA/turn; 500 kA, Total
Total NI:	7.5 Mat
B_T at Core Center (1 m):	1.4 Tesla
ESW Capability:	4.5 msec
Rep Rate:	180 seconds
TF Coil System Resistance:	0.8 m Ω
TF Coil System Inductance:	3.6 μ H
Maximum I^2Rt :	0.9 MJ
$1/2 L I^2$	0.45 MJ
Total Energy:	1.35 MJ
GPM for System at $p = 120$ psi:	2.4
Max Copper Temperature:	51.2°C
Conductor Type and Size:	127,000 circular mil (0.0997 sq. in.) copper cable with an internal copper tube for water cooling; polyethylene insulation

TABLE 3
POLOIDAL FIELD WINDING PARAMETERS

Total Turns:	6
Max Current:	83.3 kA/turn (500 kA total through 6 turns in parallel)
Total NI:	0.5 Mat
ESW Capability:	4.5 msec
Rep Rate:	180 sec
PF System Resistance:	0.38 m Ω
PF System Inductance:	3.26 μ H
Maximum I^2Rt :	0.43 MJ
$1/2 L I^2$	0.48 MJ
Total Energy:	0.838 MJ
System GPM at $p = 120$ psi:	3.6
Max Copper Temperature:	51.2° C
Conductor Type and Size:	127,000 circular mil (0.0997 sq. in.) copper cable with an internal copper tube for water cooling; polyethylene insulation

TABLE 4

S-1 EQUILIBRIUM FIELD COIL DATA

COIL NO.	NO. TURNS	MEAN RADIUS IN./M.	COPPER AREA IN ²	RESISTANCE m (20°)	T PULSE °C	GPM AT P =120psi	MAX CU TEMP °C	I _p KA	ESW SEC	REP RATE SEC	COPPER WT LBS	(kA ² /in ²)
EF-1A	14	31.496/0.80	0.907	2.071	11.4	2.9	30.9	20	2	180	812	22
EF-1B	14	31.496/0.80	0.907	2.071	11.4	2.9	30.9	20	2	180	812	22
EF-2A	15	59.055/1.50	0.907	4.16	11.4	1.75	62.8	20	2	180	1627	22
EF-2B	15	59.055/1.50	0.907	4.16	11.4	1.75	62.8	20	2	180	1627	22
EF-3A	9	71.388/1.81	0.907	3.015	11.4	2.093	44.4	20	2	180	1181	22
EF-3B	7	70.669/1.795	0.907	2.66	11.4	2.25	39.6	20	2	180	1040	22
EF-3C	5	70.394/1.788	0.907	1.65	11.4	2.94	27.8	20	2	180	647	22
EF-4	1	35.040/0.89	0.844	0.22	57.3	3.15	65.9	40	2	180	74	47.4

TOTAL SYSTEM WT: 15,640 lbs.

TOTAL COOLANT FLOW RATE: 39.5 GPM

NOTE: Two of each coil type exists due to symmetry about the mid-plane of the device. Maximum steady-state current rating = 2.5 KA at T_{coil} maximum = 79.4°C (143°F), (limiting coil - EF 2A and 2B).

TABLE 5

ACCIDENT MODES

Component	Function	Accident Mode	Accident Detection & Effect Corrective Action
Hydrogen	Fuel for Plasma	Accidental release	Because of the small quantity fire and/or explosion hazard is virtually nil.
Toxic Materials	Not Used		
Pressurized Gas	Fuel for Plasma	Bottle Explosion	Small inventory minimizes risk. Firm support required to eliminate accident.
Compressed Air	Maintenance Aid	Pressure Line Break	Conservative Design. Recessed Installation.
High Pressure Water	Cooling Water	Line Break	Conservative Design. Recessed Installation.
Radioactive Materials	Not Used		
Vacuum Vessel	Experimental Facility	Break or crack	Conservative design. Effect not dangerous, consequences will not endanger people.
Capacitor	Energy Storage	Rupture or Explosion Releases oil	Enclosed in 2 hour fire vault. Energy dissipated in capacitor is limited by circuit design. Probability of explosion low. Fire vault is armored with expanded metal mesh, containing flying parts.

TABLE 6

ACCIDENT MODES

Component	Function	Accident Mode	Accident Detection & Effect Corrective Action
Electrical Bus	Power Conduction	Short Circuit	Conservative design makes occurrence probability low. Surrounded by enclosure to prevent line of sight damage.
Coils	Experimental Equipment	Short Circuit	Conservative design. Area surrounded by walls.
Plastic Conduit	Encloses	Fire	Fire Protection and early fire detection installed.
Oil	Insulating component in capacitors	Capacitor Rupture	Enclosed in 2 hour fire vault. Fire protection, fire detection minimizes consequences.
Electrical Components	Experimental Equipment	See Failure Mode Analysis	See Failure mode analysis.

TABLE 7

S-1 FAILURE MODES

<u>FAILURE MODE</u>	<u>EFFECT</u>	<u>TF DETECTION</u>	<u>PROTECTION</u>
Short circuit on switching	Capacitor fails to charge or -if charged	Uneven charging High ignitron current	Prevent next cycle. Alarm.
Short circuit on coaxial cables	Current imbalance in the machine coil	Current shape changes High ignitron current	Prevent next cycle. Alarm.
Short circuit on collector plates	Current imbalance in flux core High ignitron current Possible flux core damage	Current shape changes High ignitron current	Prevent next cycle. Alarm.
Short circuit on TF coil	Current imbalance High ignitron current Possible flux core damage	Current shape changes High ignitron current	Prevent next cycle. Alarm.
Open TF lead	Disastrous force imbalance Flux core damage	Current shape changes Vacuum pressure increases	Prevent next cycle. Alarm.
Open one coaxial cable	Some current imbalance	Current shape changes	Prevent next cycle. Alarm.
Water flow stopped on ignitron	Decreased ignitron life	Flow switch alarm	Prevent next cycle. Alarm.
Water flow stopped on coil	Overheating machine coil	Flow and temperature switch	Prevent next cycle. Alarm.
Crowbar breaks down in the wrong direction No back-up crowbar	High ignitron current	High ignitron	Prevent next cycle. Try to fire all crowbars, they will - eventually. Alarm.
Capacitor short during charging	Uneven charging or rapid discharge	Uneven charging	Prevent next cycle. Alarm.
Capacitor short during discharge	High ignitron current Personnel hazard	"Pigtail" fault indicator blown	Prevent next cycle. Protective resistor built in to prevent explosion. Alarm. (See Failure to discharge capacitors).

TABLE 8

S-1 FAILURE MODES

<u>FAILURE MODE</u>	<u>EFFECT</u>	<u>TF DETECTION</u>	<u>PROTECTION</u>
Protective Resistor short	Capacitor fails to charge	Uneven charging	Prevent next cycle. Alarm.
Ground fault on capacitor	High ground current	Ground fault detector on charging supply	Prevent next cycle. Alarm.
Ground fault on ground switch	High ground current	Ground fault detector on charging supply	Prevent next cycle. Alarm.
Ground fault on coaxial cables	High ground current	Current imbalance	Prevent next cycle. Alarm.
Ground fault on coils	High ground current	Ground fault detector on machine	Prevent next cycle. Alarm.
Failure to discharge the capacitor	Damage to grounding switch Personnel safety compromised	Uneven voltages	Prevent next cycle. Alarm. Block access to area.
Uneven charge on the bank segments Control or rectifier failure	Unreliable ignitron firing Changed current shape	Uneven voltages	Prevent next cycle. Check control failure. Alarm.

TABLE 9

S-1 FAILURE MODES

<u>FAILURE MODE</u>	<u>EFFECT</u>	<u>PF DETECTION</u>	<u>PROTECTION</u>
Short circuit on switching Modules	Capacitor fails to charge or -if charged discharges rapidly High ignitron current	Uneven charging High ignitron current	Prevent next cycle. Alarm.
Short circuit on coaxial cables	Current imbalance in the machine coil High ignitron current	Current shape changes High ignitron current	Prevent next cycle. Alarm.
Short circuit on collector plates	Current imbalance in the machine coil High ignitron current Possible damage to flux core	Current shape changes High ignitron current	Prevent next cycle. Alarm.
Short circuit on PF coil	Current imbalance High ignitron current Possible damage to flux core	Current shape changes High ignitron current	Prevent next cycle. Alarm.
Open PF lead	Disastrous force imbalance Damage to flux core	Current shape changes Vacuum pressure increases	Prevent next cycle. Alarm.
Open one coaxial cable	Some current imbalance	Current shape changes	Prevent next cycle. Alarm.
Water flow stopped on ignitron	Decreased ignitron life	Flow switch alarm	Prevent next cycle. Alarm.
Water flow stopped on coil	Overheating machine coil	Flow and temperature switch	Prevent next cycle. Alarm.
Crowbar breaks down in the wrong direction No back-up crowbar	High ignitron current	High ignitron current	Prevent next cycle. Try to fire all crowbars, they will - eventually. Alarm.
Capacitor short during charging	Uneven charging or rapid discharge	Uneven charging	Prevent next cycle. Alarm.
Capacitor short during discharge	High ignitron current	"Pigtail" fault indicator blown	Prevent next cycle. Protective resistor built in to prevent explosion. Alarm.

TABLE 10

S-1 FAILURE MODES

<u>FAILURE MODE</u>	<u>EFFECT</u>	<u>PF DETECTION</u>	<u>PROTECTION</u>
Protective Resistor short	High ignitron current	High ignitron current	Prevent next cycle. Alarm.
Ground fault on capacitor	High ground current	Ground fault detector on charging supply	Prevent next cycle. Alarm.
Ground fault on grounding switch	High ground current	Ground fault detector on charging supply	Prevent next cycle. Alarm.
Ground fault on coaxial cables	High ground current	Current imbalance	Prevent next cycle. Alarm.
Ground fault on coils	High ground current	Ground fault detector on machine	Prevent next cycle. Alarm.
Failure to discharge the capacitor	Damage to grounding switch Personnel safety compromised	Uneven voltages	Prevent next cycle. Alarm. Block access to area.
Uneven charge on the bank segments Control or rectifier failure	Unreliable ignitron firing Changed current shape	Uneven voltages	Prevent next cycle. Check control failure. Alarm.

TABLE 11

S-1 FAILURE MODESFIRING CIRCUIT FAILURES

<u>FAILURE MODE</u>	<u>EFFECT</u>	<u>TF DETECTION</u>	<u>PROTECTION</u>
Failure to fire	Aborted pulse or crowbar protection absent	Low ignitron current	Prevent next cycle. Provide back-up firing. Alarm.
False firing	Aborted pulse or missing crowbar	Abnormal (either low or high) ignitron current.	Prevent next cycle. Provide back-up firing. Alarm.
Shock hazard on firing circuit	Firing circuit fails to discharge	Charge indicator	Prevent next cycle. Alarm.
Acid drop from battery	Corrosion	Corrosion	Replace battery
Firing transformers break over	Short circuit on capacitors False firing of ignitrons	High ignitron current. Uneven charge.	Prevent next cycle. Alarm.

TABLE 12

S-1 FAILURE MODES

<u>FAILURE MODE</u>	<u>EFFECT</u>	<u>EF DETECTION</u>	<u>PROTECTION</u>
Water flow	Overheating	Flow switch, temperature switch	Flow switch prevents pulse. Alarm.
Overheating	Elevated temperature	I ² t protection, temperature switches	Prevent next cycle. Alarm.
Overcurrent	Excessive force Possible damage to EF coils, bus, and vacuum vessel EF current should not exceed 22 kA	Overcurrent, voltage, and time monitoring	Trip MG breaker. Alarm.
Ground fault	Ground current	Ground fault detector	Trip MG breaker. Alarm.
Patch panel connection faulty	Improper coil feed Possible damage to EF coils, bus, and vacuum vessel EF current should not exceed 20 kA	Patch panel interlock	Prevent cycle. Alarm.

TABLE 13

S-1 FAILURE MODES

<u>FAILURE MODE</u>	<u>EFFECT</u>	<u>DETECTION</u>	<u>PROTECTION</u>
Vacuum leak seals, welds, etc.	Excessive pressure May damage T.M.P.'s & roots blowers	Ion Gauge/T.C.'s	Close high vacuum and foreline valves. Alarm.
Inconel liner fails vacuum leak	Excessive Pressure & high impurity level	Ion Gauge, RGA or mass spectrometer	Close high vacuum and foreline valves. Alarm.
Liner overtemp.	Overstress of liner Delamination, buckling	Liner T.C.'s (75°F) Prior to pulse	Inhibit pulse until TC's reach 75°F. Alarm.

TABLE 14

S-1 FAILURE MODESPF IGNITRONS

<u>FAILURE MODE</u>	<u>EFFECT</u>	<u>DETECTION</u>	<u>PROTECTION</u>
1 forward ignitron fails to fire.	Rest of the bank reverses, failed ignitron breaks over. Capacitor section overcharges. Also excessive current in the ignitron.	1 forward ignitron failed to conduit. Time frame noted.	Overvoltage protection across each capacitor segment, in explosion-proof enclosure. Back-up and redundant firing-- if the trouble is with the firing circuit. Alarm signal, cause to be investigated.
1 forward ignitron fires prematurely.	One segment of the bank reverses. All segment ignitrons are overvoltaged and break over. Capacitor section overcharges. Also excessive current in the ignitron.	1 forward ignitron conducts prematurely; Time frame noted.	Fire all forward ignitrons if any of them start conduction. Alarm signal.
1 crowbar ignitron fails to fire.	Less flat top More liner heating.	1 crowbar ignitron fails to conduct. Time frame noted.	Redundant firing - in case this trouble is with the firing circuit alarm signal. There are eight crowbar tubes, one tube firing is enough to protect the liner.
1 crowbar ignitron breaks over prematurely in its forward direction.	Short circuit current flowing through the failed ignitron.	1 crowbar ignitron conducts fire prematurely. Time frame noted.	Fire crowbar ignitrons that can conduct to share the current. Alarm signal.
1 crowbar ignitron breaks over in reverse direction.	Short circuit current flow through its failed ignitron.	1 crowbar ignitron conducting prematurely in the reverse direction. Time frame noted.	Fire crowbar ignitrons that can conduct to duct to share the fault current. Alarm signal.

TABLE 15

S-1 FAILURE MODES

<u>FAILURE MODE</u>	<u>EFFECT</u>	<u>DETECTION</u>	<u>PROTECTION</u>
TF main crowbar ignitron breaks over (in the conducting direction while the TF main bank is conducting)	Short circuit current will flow through the crowbar ignitron.	Premature conduction of one TF main crowbar ignitron. Time frame noted.	Fire all like crowbar ignitrons to share the current. Alarm signal.
TF Main crowbar ignitron breaks over (in the reverse direction while the TF main bank is conducting)	Short circuit currents will flow through this crowbar ignitron.	Premature conduction of one TF main crowbar ignitrons. Time frame noted.	Fire all crowbar ignitrons with the failed one to share this current. Alarm signal.
1 TF main forward Ignitron fails to fire	The rest of the bank reverses, overvoltages the TF bank segment. Also excessive current in the ignitron.	Failure of one TF main ignitron to fire. Time frame noted.	Redundant firing signal, in this case this firing circuit failed. Overvoltage protection across the TF capacitor bank, in explosion-proof enclosure. Alarm signal.
1 TF main crowbar ignitron fails to fire.	Less flat top More liner heating.	Failure of one TF crowbar ignitron to fire. Time frame noted.	Redundant firing signal, in case the firing circuit failed. There are eight crowbar ignitrons, one tube firing is enough to enough to protect the liner. Alarm signal.

TABLE 16

AUXILIARY SYSTEMS POWER DISTRIBUTIONFAILURE MODE AND EFFECTS ANALYSIS

Component	Function	Failure Mode	Failure Effect/Corrective Action
1. Feeder Circuit Breakers	Connects feeder to switchgear bus	A) Failure to close	A) No power to feeder. Supply auxiliary power with an alternate feeder and circuit breaker.
		B) Overheating, poor contacts	B) No power to feeder. Supply auxiliary power with alternate feeder and circuit breaker. Check load on circuit. Preventive maintenance will minimize occurrence.
		C) Explosion	C) No power to feeder, damage to switchgear, and potential fire. Supply auxiliary power with diesel generator on alternate feeder. Extinguish fire. Check overcurrent relays and load on circuit. Preventive maintenance will minimize occurrence.
2. Feeder Cable	Connects subsystem system to feeder	Short circuit; grounded	Trips circuit breaker. Supply power with alternate feeder. Prevent through periodic inspection.
3. Transformers	Energizes bus	Internal short circuit	Primary fuse blows; no power supplied to bus by affected transformer. Supply loads through alternate transformer.
4. Substation Circuit Breakers	Connects transformer to bus	Failure to close, overheating, or poor contacts	No power to load through affected substation breaker. Supply loads through alternate transformer and its substation breaker.

TABLE 17

DIESEL GENERATOR SYSTEM FAILURE MODES AND EFFECTS ANALYSIS

Component	Function	Failure Mode	Failure Effect/Corrective Action
1. Diesel Generator Support Systems (Fuel Oil, Lube Oil, Cooling Water, & Start-up Systems)	To start the diesel engine and maintain the engine temperature, lubrication, and fuel oil at optimum operating levels	Failure to carry out required function	Detected by affected support system parameter monitors, and/or by generator speed monitor. Diesel engine fails to start or is shutdown automatically [see note (a) below].
2. Diesel Generator Breaker	Connects diesel generator to bus	Failure to close on command, overheating, or poor contacts	Absence of current in 480 V subsystems detected by load feeder ammeters, and 480 V switchboard bus feeder wattmeters, voltmeters and/or ammeters. Diesel generator cannot supply power [see note (a) below].
3. Cable Intertie	Connects diesel generator breaker	Short or open circuit	Failure causes trip of generator breaker. Diesel generator cannot supply power [see note (a) below].
(a) In the unlikely event that primary power distribution fails and the diesel generator fails to start, operate, or deliver power, the facility will go into a safe shutdown status. This means that by way of the hardwired interlocks required of each system the power supplies will shut down, energy will be dissipated safely, valves to vacuum systems will close. In addition, safety-related monitoring systems will be on uninterruptible power thus giving status information and enabling safe recovery of systems.			

TABLE 18

PULSED ENERGY CONVERSION SYSTEMFAILURE MODES AND EFFECTS ANALYSIS

Component	Function	Failure Mode	Fault Detection & Effect/Corrective Action
Capacitor Bank		A) One capacitor in a capacitor bank is shorted internally.	A) The affected capacitor's fuse will blow and less energy will be available to build up the load current. Detected by visual (fuse) indicator during inspection. Repair before next experiment.
		B) The terminals of a capacitor bank are shorted together.	B) The capacitor charger will be shorted out, resulting in smaller charge in the total capacitor bank, which may affect the plasma operation. Detected by voltage magnitude signal. The protection system of the charger supply will operate to disconnect the charger. Repair before next experiment.
		C) Dump switch closes accidentally.	C) Near short circuit across charger terminals, detected via signal (ground switch status). Charger protection system will remove charger from the system. Repair before next experiment.
4. Capacitor Charge and Discharge System	Charging and discharging the capacitor	A) The charger does not supply voltage.	A) Results in smaller charge in the total capacitor bank, which may affect the normal plasma compression. Detected by voltage magnitude signal. Repair before next experiment.

TABLE 19

S-1 POST OPERATIONAL PHASE - ASSURANCE CONTROLS

SAFETY RELATED SUBSYSTEM/COMPONENT	CHANGE CONTROL	SAFETY AUDITS	PROCEDURES	CALIBRATION PROGRAM (*)	TEST	ASSURANCE RECORDS/DOCUMENTATION
I. EF Coil	1A 5C	NA	Sec. VIII	1A 5C 2C	1A	1A
II. PF Coil	1A 5C	NA	Sec. VII	1A 5C 2C	1A	1A
III. TF Coil	1A 5C	6A	Sec. VII	1A 5C 2C	1A	1A
IV. Water Cooling	1A 5C	NA	Sec. VII	1A 5C 2C	1A	1A
V. Vacuum & Gas	1A 5C	6A	Sec. VII	1A 5C 2C	1A	1A
VI. Safety	1A 5C 6C	6A	1A	NA	1A 6C, 6D	6A
VII. Operations	1A 5C 6C	6A	1A	1A 5C	NA	1A

Functional GroupResponsibility

*

1. Project Management	A. Primary	1) Electrical/Electronic Calibration Performed by Engineering
2. Engineering Management	B. Supporting	2) Mechanical Measuring Calibration Performed by PPPL QA
3. Cognizant Engineer	C. Monitoring	3) Diagnostics Calibration/Operational Calibration by Research & Project
4. Physicist, Lead	D. Assessment	
5. Quality Assurance		
6. Safety		

FLOOR PLAN - GROUND LEVEL
FIGURE 1

WEST ELEVATION

Figure 2

S-1 SPHERONAK
Figure 3

CROSS SECTION OF FLUX CORE

Figure 4

FIG. 5 FLUX CORE WINDING SCHEMATIC

#83A0054

PF/TF CRATE
FIGURE 7

83A0055

MG ROOM CRATE

FIGURE 8

AREA LA 'OUT

FIGURE 9

KEY INTERLOCK SYSTEM

FIGURE 10

SAFETY LOCK-OUT SWITCH

FIGURE 11

NOTES:

⚠ Relay contact summing closed when all disconnects are open, plus capacitor, shorting and grounding switches shown on Dwg. 6003-D-50020-EM, Sh. 3.

⚠ The power to various devices described above is routed through these contacts.

SCHEMATIC FOR EF FIELD INDICES MODE A MODE B MODE C
N=0.033, N=0.060, N=0.124 (TABLE A)

DIAGRAM A

NOTE: EF COILS 1&2 ARE MADE UP OF INDIVIDUAL PANCAGES A&B, EF COIL 3 IS MADE UP OF INDIVIDUAL PANCAGES A,B&C. SEE TABLE B. THERE ARE TWO OF EACH COIL (NORTH & SOUTH) LOCATED COAXIALLY AND SYMMETRICALLY ON BOTH SIDES OF THE FLUX CORE.

TABLE B

COIL NO	NO OF TURNS	COIL RESISTANCE (mΩ)	Rated I (A)	Rated Z (mΩ)
EF-1A	14	0.071	1.000	1.000
EF-1B	14	0.071	1.000	1.000
EF-2A	15	0.060	1.500	1.000
EF-2B	15	0.060	1.500	1.000
EF-3A	10	0.104	1.000	1.000
EF-3B	10	0.104	1.000	1.000
EF-4	1	0.22	0.80	0.0358

REF 1074

DIAGRAM B

TABLE A

NO OF TURNS REQUIRED FOR COIL AT VARIOUS FIELD INDICES

COIL NO	MODE A N=0.033	MODE B N=0.060	MODE C N=0.124	MODE D N=0.354
EF-1A	0	0	-14	-14
EF-1B	0	-14	-14	-14
EF-2A	-15	0	0	-15
EF-2B	-15	-15	0	-15
EF-3A	0	0	0	0
EF-3B	0	0	0	0
EF-4	0	0	0	0
EF-4	0	0	0	0

DIAGRAM A

TABLE C
LOAD CHARACTERISTICS AT MODES A,B,C,&D.

	MODE A N=0.033	MODE B N=0.060	MODE C N=0.124	MODE D N=0.354
LOAD R (mΩ)	11.735	9.943	8.101	39.57
LOAD L (mH)	37.4	30.0	21.8	31.7
FLIP (sec)	3.70	2.47	2.4	3.3
TOT. ENERGY (J)	21.3	32.5	24.2	15.2
FLIP (sec)	400	375	272	701
TIME CONSTANT (sec)	0.394	0.330	0.440	0.440

EF SYSTEM CONFIGURATION
FIGURE 12

#83A0059

1. Kirk Key is in MG Patch Panel.
2. Kirk Key #SK7 on door.
3. Kirk Key #SK6 on door.

FIGURE 13

EF SYSTEM BLOCK DIAGRAM
FIGURE 14

83A0052

S1 EF STATE DIAGRAM
FIGURE 15

PF/TF POWER SUPPLIES
FIGURE 16

PF/TF SYSTEM BLOCK DIAGRAM
FIGURE 17

83A0053

S1 PF/TF STATE DIAGRAM

FIGURE 18

#83A0058

SCHEMATIC DIAGRAM OF THE S-1 PUMPING SYSTEM

FIGURE 19

WATER VALVE CONTROL

FIGURE 20

UNIVERSITY CONTRACTOR, GRANTEE AND COOPERATIVE AGREEMENT
RECOMMENDATIONS FOR ANNOUNCEMENT AND DISTRIBUTION OF DOCUMENTS

See Instructions on Reverse Side

1. DOE Report No. PPPL-2083	3. Title Safety Assessment for the S-1 Spheromak
2. Contract No. DE-AC02-76-C110-3073	
4. Type of Document ("X" one) ☒ a. Scientific and technical report ☐ b. Conference paper: Title of conference _____ Date of conference _____ Exact location of conference _____ Sponsoring organization _____ ☐ c. Other (Specify planning, educational, impact, market, social, economic, thesis, translations, journal article manuscript, etc.) _____	
5. Recommended Announcement and Distribution ("X" one) ☒ a. DOE's normal announcement and distribution procedures may be followed. ☐ b. Make available only within DOE and to DOE contractors and other U.S. Government agencies and their contractors.	
6. Reason for Recommended Restrictions _____	
7. Patent and Copyright Information Does this information product disclose any new equipment, process or material? ☒ No ☐ Yes If so, identify page nos. _____ Has an invention disclosure been submitted to DOE covering any aspect of this information product? ☒ No ☐ Yes If so, identify the DOE (or other) disclosure number and to whom the disclosure was submitted. Are there any patent-related objections to the release of this information product? ☒ No ☐ Yes If so, state these objections Does this information product contain copyrighted material? ☒ No ☐ Yes If so, identify the page numbers _____ and attach the license or other authority for the government to reproduce.	
8. Submitted by Barbara Pavelec	Name and Position (Please print or type)
Organization Princeton Plasma Physics Laboratory	
Signature <i>Barbara Pavelec</i>	Date 3/21/84

FOR DOE OR OTHER AUTHORIZED
USE ONLY

9. Patent Clearance ("X" one)
☒ a. DOE patent clearance has been granted by responsible DOE patent group.
☐ b. Report has been sent to responsible DOE patent group for clearance.

INSTRUCTIONS

MAR 23 10 00 AM '84
 TECHNICAL INFORMATION CENTER

Who uses this form: DOE contract administrators will designate the DOE contractors and grantees who are to use this form. Generally speaking, it will be used by educational institutions and other "not for profit" institutions. DOE national laboratories and other major contractors will generally use the longer Form RA-426.

When to use: DOE contractors are required under their contracts to transmit specified types of documents to the DOE. Some, but not all, of these are transmitted by DOE contract administrators to the DOE Technical Information Center (TIC) and may be incorporated into the DOE technical information documentation system. Types of documents that will be transmitted to TIC are identified in instructions that the contractor receives from his contract administrator. Each such document is to be accompanied by one copy of this transmittal form recommending to TIC appropriate announcement and distribution of the document. Documents which the contractor may be required to submit to the DOE under his contract but which are not of the type to be transmitted to TIC, e.g., contract proposals, should not be accompanied by a copy of this transmittal form.

Where to send: Send the document and the attached Form RA-427 to the DOE contract administrator for transmittal to TIC unless the DOE contract administrator specifies otherwise.

Item instructions:

Item 1. The DOE report number will be constructed as follows and will consist of a prefix and a suffix. The prefix will consist of code DOE and seven characters for the applicable contract number (two alphabetic and five numerical). The suffix is a sequential number assigned by the contractor generating the report. Slashes and hyphens will be used as shown in the examples in the next column.

Reports issued in more than one binding or reissued as revisions on later editions will be identified by adding the additional suffixes to the basic number: e.g., Rev., Revision; Vol., Volume; Pt., Part; Add., Addendum; Ed., Edition.

Examples

If the contract number is DE-AC01-76RA01834.M002, the reports generated will be numbered:

DOE/RA/01834-1
 DOE/RA/01834-2
 DOE/RA/01834-2 Rev.1

(The modification number, if any, normally shown as .M002, etc., following the basic five-digit number, is not used in the report number.)

- Item 2.** Self-explanatory.
- Item 3.** Give title exactly as on the document itself.
- Item 4.** Self-explanatory.
- Item 5.** The "normal announcement and distribution procedures" for unclassified documents may include abstracting in *Energy Research Abstracts (ERA)* and distribution to appropriate DOE/TIC-4500 ("Standard Distribution of Unclassified Scientific and Technical Reports") addressees, to libraries that through purchase of microfiche maintain collections of DOE reports, and to the National Technical Information Service (NTIS) for sale to the public. Check 5b if there is need for limiting announcement and distribution procedures described above.
- Item 6.** Self-explanatory.
- Item 7.** Self-explanatory.
- Item 8.** Enter name of person to whom inquiries concerning the recommendations on this form may be addressed.
- Item 9.** DOE contract administrator or patent group representative should check a or b and forward this form and document to:
 USDOE-TIC
 P.O. Box 62
 Oak Ridge, TN 37830