

PFC/RR-81-29

DOE/ET/51013-23

UC20 B

Cycle Design for a Cryogenic Refrigeration
System for FED with Forced Flow Superfluid Helium
through Internally Cooled Conductors

by

Joel H. Schultz

M.I.T. Plasma Fusion Center
O.R.N.L. Fusion Energy Design Center

**Cycle Design for a Cryogenic Refrigeration System for FED
with Forced Flow Superfluid Helium through Internally Cooled Conductors**

by Joel H. Schultz

M.I.T. Plasma Fusion Center

O.R.N.L. Fusion Energy Design Center

M.I.T. Research Report PFC/RR-81-29

**Cycle Design for a Cryogenic Refrigeration System for FED
with Forced Flow Superfluid Helium through Internally Cooled Conductors**

by Joel H. Schultz

M.I.T. Plasma Fusion Center

O.R.N.L. Fusion Energy Design Center

ABSTRACT

A cryogenic refrigeration system has been designed for the specifications of the magnet system of the Fusion Engineering Device (FED). The unusual specification of an internally cooled cabled niobium titanium superconductor at a maximum field of 10 tesla, coupled with high ac losses and high neutron and gamma heating in the toroidal field coils led to the selection of a cooling system with superfluid helium at the inlet to the toroidal field coils. While highly unusual as a coil-cooling concept, the implications for the refrigeration system were not unfavorable and showed several features of interest. Among the favorable comparisons with "conventional" supercritical flow systems were reduced entropy generation in the coil due to pressure drops. However, the low inlet temperature and the high losses combined to require 63 MW of room temperature work on the helium, about 4 times that of the Isabelle refrigeration system, which the FED system resembles.

A. Cryogenic Refrigerator System Function Summary

The cryogenic load for the Fusion Engineering Device is complex, consisting of losses removed by circulating superfluid and supercritical helium through the toroidal field windings, circulating supercritical helium at different temperatures through the inside of the toroidal field coil cases and the intercoil structures, and by pool-boiling of atmospheric pressure helium in the poloidal field coils and cases. A summary of the loads is presented in Table I. The refrigerator design is determined by the loads for the 10 tesla extended performance case which are larger than those for the 8 tesla scenario for all systems. Since the coolant has significantly different inlet and outlet thermodynamic states for each of the cryogenic loads, the only common basis for comparison of the loads is the rate of entropy generation [SM80], which is shown in the table. The single largest load is that generated in the winding of the TF coils, but the winding losses, case losses and intercoil structure losses of the toroidal field system are all significant. The entropy generation of the FED system load is several times higher than that of any existing or planned cryogenic refrigeration facility in the world, being 3.3 times larger than that projected for the ISABELLE intersecting storage ring accelerator at Brookhaven [SC80], which is currently the largest planned refrigeration system.

The largest single heating load is 46.3 kW of ac losses into the intercoil structure. While this load is half of the total cryogenic losses, it only constitutes 20 % of the load entropy generation, because the heat is removed at moderately high temperatures. Further design iterations should be able to identify appropriate lower stress regions in which more thermal or electrical insulation breaks could be added, in order to eliminate the significance of this load. The second largest load is that taken by the inner case channels. These channels, between the coil case and the winding pack, are similar to those proposed for Tore Supra. They intercept losses in the hotter case and prevent the requirement to remove them through the cooler winding pack. Losses in the case include ac pulsed magnetic field losses, neutron and gamma heating and conduction from the hotter outer case channels and intercoil structure. These losses can only be substantially reduced by significant changes in the design structure. Neutron and gamma losses can be halved by adding a sufficient amount of boron to the shield, as explained in section ... Further reductions require increases in the shield thickness and machine size. AC losses in the case can only be decreased substantially by laminating the case or by the use of an internal bolted plate construction, as used in the Westinghouse LCP concept, which removes the need for a thick external case.

The most unusual aspect of the load of the reference design is the use of a forced-flow, NbTi conductor with a superfluid inlet and a supercritical fluid outlet coolant. The mission of enhanced plasma performance at 10 T can be achieved by the use of Nb₃Sn in a graded conductor or inserts or by the use of pool-boiling subcooled or superfluid helium. Insufficient analysis, experiment or development work has been done to justify the specification of the reference concept described above. In fact, we know of no magnet, however small, that employs it. In contrast with an all supercritical helium system, this concept should have the disadvantage of a requirement for a complicated inlet headering system with many independent feeds in order to avoid large flow instabilities due to uneven heating of different coolant channels. However, the concept does have an attractive rationale which justifies its exploration. All of the alternatives have disadvantages which can be argued outweigh the expense of a complex headering system. A forced-flow, jacketed conductor allows a fully insulated conductor concept which can eliminate the most common cause of magnet failure, electrical breakdown due to tracking or metal chips. This topology also allows the use of high surface area cable without any stress concentrations or risk of creep indentation of the conductor against the insulation. The use of NbTi eliminates the need for Nb₃Sn, which has higher cost, has yet to establish adequate mechanical properties in a large magnet and may not be capable of establishing high strength joints to NbTi in a jacketed cable. The use of a superfluid bath is limited to a steady-state heat removal rate, through a long vertical channel the height of the FED TF coils, of about 1 W/cm² of helium. This appears to be inadequate for the FED heat load, if either the General Dynamics or General Electric LCP conductors are used, although it should be adequate for the General Electric 12 tesla conductor, considered earlier for the Engineering Test Facility [ST80].

The use of a forced-flow conductor with a maximum outlet temperature of about 3.0 K has the one major limitation that, at the lower pressure limit of about 2.25 atmospheres for supercritical fluid behaviour, the specific enthalpy of helium is only 6.3 J/g. This contrasts with a specific enthalpy of 30 J/g for helium vapour at 4.2 K or 31.3 J/g at 2.3 atmospheres and 5.5 K, such as has been proposed for high performance forced-flow magnets using Nb₃Sn. Thus a much higher mass flow is required for the same amount of cooling capacity. Furthermore, since the Joule-Thomson coefficient is unfavourable in this regime, raising the fluid temperature as pressure drops, there is an absolute limit on the amount of heat that can be removed through a given channel for a given desired outlet state. In the reference design, by using an inlet in the superfluid regime, 1.85 K and 4.0 atmospheres, a conservative design is possible from the standpoint of steady-state heat

removal. The inlet enthalpy is 3.7 J/g, while the outlet enthalpy at 3.2 K and 2.3 atmospheres is 6.8 J/g, so 3.1 J/g can be removed, with a pressure drop of 1.7 atmospheres. If the average pressure drop, integrated over a hydraulic channel, is half that at the outlet, we calculate that a mass flow of 5.8 g/s could be achieved, allowing the removal of 18 W per channel, or 8.5 W/cm². Since the average loss per turn is 2.0 W and there are 3 turns per hydraulic channel, this allows a peaking factor of 3 for the hottest channel. By contrast, a 1.7 atmosphere drop with an inlet of 2.5 K supercritical helium would not permit removal of any heat at all in the range of 2.3 to 20 atmospheres outlet pressure, and there would be no benefits from lower pressure drops in the superfluid region.

The low, although not really zero, viscosity of helium in the superfluid regime allows the possibility that the refrigeration load in the TF coil using a superfluid inlet may actually be lower than if a higher temperature inlet fluid were used. The largest term in the entropy generated by the assumed drop from 4.0 atmospheres to 2.3 atmospheres is that due to isenthalpic throttling, the Joule-Thomson effect. If the entire externally imposed heat load were removed through boiling at 2.0 K, the entropy generation would only be 4,625 W/K. The calculation that the entropy generation of the TF system in the reference design is 9,892 W/K assumes that the pressure drop from the inlet to the outlet header is that of the worst case channel. However, in fact, the cooler channels will remain superfluid longer and will have a lower pressure drop. Independent circuits will be necessary to prevent the superfluid channels from shunting flow from the supercritical channels at the outlet header. However, during the normal operating conditions at 8.0 T where neutron and gamma heating, the second largest terms, are reduced by a factor of 2.5, all channels should remain superfluid with entropy generation rates far lower than a channel moving 5.8 g/s of all supercritical helium at 3.0 K through the TF winding with no external heat generation at all. If the concept of forced-flow heat removal with a superfluid inlet is retained, an attempt should be made to investigate whether the desirable feature of low pressure drop for high mass flow can be included in the design for most of the channels for all modes of operation. If this can be accomplished, it would reduce the room temperature power requirements for TF winding refrigeration by at least the factor of two calculated above.

B. Refrigerator Line Diagram

The refrigerator concept examined for FED is derived from the refrigeration system for the ISABELLE

intersecting storage ring accelerator, to be built at Brookhaven [BR81]. A line diagram of the refrigeration system is shown in Figure I. A table of the entropy generated by each component in the refrigeration system is given in Table II. A table of temperatures and pressures at all of the labeled interface points is given in Table III. A variant of the ISABELLE refrigerator was selected because of several similar features in the two systems, including the use of subcooled, forced-flow supercritical helium and the enormous size. Significant features include:

- (1) a high pressure closed coolant loop for the TF coils, cooled by baths at 3 different temperatures.
- (2) separate loops for the PF coils and the TF case,
- (3) return of the outlet fluid from the inside of the TF cases through the outside and intercoil structures.
- (4) the use of cold compressors to interface the return stream with a high pressure counterflow heat exchanger chain, and
- (5) the absence of any nitrogen loops from a closed loop helium system.

Two expansion stages are used in the heat exchanger chain, with a third expander for the forced-flow TF case loop and a Joule-Thomson valve for the main helium feed to the 3 baths cooling the cold high pressure loop for the TF windings.

Almost all of the components in the refrigerator design will have been previously tested in ISABELLE and other large refrigeration systems, such as the Fermilab Energy Doubler, MFTF-B and LCP. However, the compressor C4, with an inlet of 1.85 K and .016 atmospheres would require a separate development program. A similar development program is being sponsored by the ISABELLE program for the 2.65 K cold compressor in their design. If the assumed efficiency of the compressor in the reference design can be achieved, cold compressor C4 contributes less than 1 % of the total system entropy, so there should be considerable tolerance for a less efficient compressor design, if necessary.

C. Design Selection and Alternate Concepts

The refrigerator design presented here is the first cut at a self-consistent design and does not represent any attempt to optimize or to justify selection of a topology from among different alternatives. Work is in progress on a refrigeration systems analysis and sizing code, for which most of the component models have been completed. Given the complexity of the refrigerator specification, quantitative comparison between alter-

native approaches is not attractive without automated numerical design aids. As will be discussed in section E, a study of the entropy generation table reveals two obvious improvements for the reference refrigerator topology. Certain design considerations, however, did lead to the reference topology.

The major component trade-offs in the design included the use of cold compressors vs. the use of larger heat exchangers and transfer lines and the use of wet expanders vs. the use of Joule-Thomson valves. A topological consideration was whether to use a high pressure, warm circulator system for the forced-flow coolant, as is done for LCP, or a cold circulator with cooling by low pressure baths. Cold compressors were chosen over oversized helium transfer components because of the extremely large sizes of heat exchanger return paths and cryogenic transfer lines required at 0.016 atmosphere. If the compressors work with an isentropic efficiency of 70 %, which is the design goal of the ISABELLE cold compressors, much less space and materials will be required for the refrigeration system, and presumably less money. Bejan [BE77] studied a similar cycle and concluded that cold compressors would be preferred over warm recirculators if the isentropic compressor efficiency was greater than 41 %. Since the FED refrigeration system, as currently defined, is slightly larger than all the other cryogenic refrigerators in the world put together, it is unlikely that a component development program, even if it were unsuccessful, would add significantly to the total cost of the system.

Wet expanders, as proposed for a helium liquefaction cycle by Minta [MI81] and as used in the Fermilab Energy Doubler satellite refrigerators [CO79] might increase the efficiency of the bath generation by Joule-Thomson valve JT3, which requires an entropy addition of 1.78 kW/K, or only about 1.4 % of the total system entropy generation. While it might be good to test out wet expanders to gain more knowledge of their long term reliability on noncommercial systems, such as FED, their use does not seem to make a sufficient difference in this design to bother supplementing the work at Fermi.

From the fundamental considerations of environmental safety and magnet shielding requirements, it is undesirable to have large, low pressure transfer lines penetrating the nuclear island. This problem is avoided in the reference design, which employs a closed high pressure loop, with all low pressure 1.85 K streams in a separate building. This is much more of a problem with pool boiling superfluid helium, where low pressure pool boiling requires penetrations on the order of 1 m diameter. Stagnant, pressurized 1 atmosphere helium, such as is proposed for the Tore Supra tokamak [AY80] has no really plausible pathways to conduct heat to a nearby external reservoir for the case of the FED TF system, with its combined high heat load, tall stack and

cluttered surroundings.

D. Refrigerator Sizing

Since the refrigerator system for the enhanced performance 10 tesla option has been designed, it does not need to be sized. Cooldown should not be a dominant factor for sizing FED refrigerator components as it was in a previous sizing exercise [SC81]. This study attempted to take advantage of a proposed very low annual integrated duty cycle (.02 %) by running the load from a liquid helium storage dewar. The method was evaluated [SC81] to save about 25 % over a refrigerator rated for steady-state removal of the heat generated over a single cycle. For the current design this approach was not reevaluated, since the increase by nearly a factor of 10 to a 17 % duty factor, coupled with the selection of forced-flow cooling, made it highly unlikely that any significant economies could be achieved by attempting to reduce refrigerator power in exchange for extra helium storage. Using a larger refrigerator, instead of larger storage, would also allow considerably more flexibility to allow experiments over more extended periods, if this became feasible. In the present design, the main compressor performs work on the helium at a rate of 63 MW, which is 4.5 times the main compressor power of the ISABELLE refrigerator, while the cold mass is only 2/3 that of the ISABELLE magnet system. The operating plan of ISABELLE is to achieve cooldown in only 360 hours, while the reference scenario for FED allows 4 weeks for cooldown. The current design will almost certainly be limited by thermal stress considerations in the large cold structural components, rather than by any lack of capacity in the refrigeration system. The previous sizing exercise [SC81] calculated that a helium flow of 4,000 l/hr would be adequate for cooldown from 100 to 20 K in two weeks and that only 1,000 l/hr would be needed for final cooldown and fill in 1 week.

E. Refrigerator Design Analysis

The principal tool used in evaluating the refrigerator design is the component entropy inventory table, Table II. The total work done on the helium by the room temperature compressor system equals the product of the entropy generated by the rest of the components and the temperature of the working fluid in the room temperature compressor. Put another way, in a system such as this one with no nitrogen, the room temperature compressor is the only component that decreases the entropy of the helium passing through it, and in a closed

system this decrease must equal all the entropy increases of the other components. Entropy generation is the only measure that can put the refrigeration requirements of heat loads at different or distributed temperatures, vaporization, liquefaction and isenthalpic pressure drops on a common basis. [SM81]

The total entropy generation of all the components in the system is 138 kW/K. This is 5.4 times the entropy generated in the load. By comparison, the ISABELLE system required 4.0 times the entropy generated in the load. The difference reflects the fact that the FED design is only a first cut, while the ISABELLE design is final. There may also be a second-order unfavourable dependence on the lowest temperature in the system, which is 1.8 K for FED and 2.65 K for ISABELLE. Of the 138 kW/K generated in the FED system, 41.1 kW/K is generated by the heat exchangers, 39.6 kW/K by the expanders, 16.7 kW/K by the Joule-Thomson valves and 12.5 kW/K by the cold compressors. These numbers imply that a reasonable balance has been achieved between cooling by heat exchange and cooling by expansion, and that the cold compressors are only increasing the system refrigeration requirements to the second-order.

A detailed look at the entropy generation of the individual components, however, does reveal two errors in temperature and mass flow selection. In the inner cold forced-flow loop, the entropy generated by Joule-Thomson valve, JT5, feeding heat exchanger HX13, is only 0.36 kW/K and the entropy generated in HX13 is only 0.83 kW/K. By contrast, the entropy generated in JT4, feeding HX12, is 10.9 kW/K and the entropy generated in HX14, the 1.8 K heat exchanger, is 3.85 K. The implication is that HX13 is not contributing enough to the three stage cooldown and that it should cool the high pressure stream to a lower temperature than 2.5 K. Similarly, at the end of the high temperature heat exchanger chain, HX10 generates an entropy of 8.27 kW/K, while the heat exchanger preceding it, HX9, is loafing along at 0.27 kW/K. The cause of this is the mass flow imbalance in the two legs of HX10. This suggests that entropy generation could be reduced by passing the inlet to expander EX4 through heat exchanger HX9, allowing the exhaust of EX4 to be returned through the cold side inlet of HX10. These two fixes might reduce the ratio of refrigerator entropy generation to load entropy generation to below 5.0.

F. Future Work

Future work in the cryogenic refrigeration system design should include cooperating with magnet structural designers and nuclear shielding designers to reduce the cryogenic load, completing a refrigerator analysis

code to more rapidly evaluate different topologies and investigating refrigerator concepts that might simplify overall machine design. One such concept mentioned above is a more detailed design of the flow in each channel to minimize the entropy generation due to pressure drops, which is the dominant refrigeration requirement of the TF windings. Another new concept would be to investigate the possibility of suspending superinsulation from the vacuum dewar wall, with no actively cooled thermal radiation shield. This would greatly simplify the internal plumbing of the cryostat, while increasing total radiation losses, which are a trivial fraction of the total load, by less than an order of magnitude. A similar recognition of the dominance of pulsed ac and nuclear radiation loads would be to reexamine an early design decision to use internal cold structure for the support of out-of-plane forces. The major motivation for cold structure is to avoid excessive heat leaks through structural support members. In the reference design, ac losses in the cold supports are over 2,000 times greater than thermal conduction losses through structural support members. The use of stacked G-10 pads recommended for gravitational load support is a possible candidate for interface with a warm support structure.

References

- [AY80] R. Aymar et al, "TORE SUPRA: Basic Design Tokamak System", Euratom Report EUR-CEA-FC-1068, Oct. 1980
- [BE77] A. Bejan, "Refrigerator-recirculator systems for large forced-cooled superconducting magnets", Cryogenics, Feb 1977
- [BR81] D.P. Brown et al, "Cycle Design for the Isabelle Helium Refrigerator", presented at 1981 ICEC Conference, San Diego, Ca, Aug 1981, to be published
- [CO79] F.T. Cole et al, "A Report on the Design of the Fermi National Accelerator Laboratory Superconducting Accelerator", Fermi National Accelerator Laboratory Report, May, 1979
- [MI81] M. Minta, "Study of Helium Liquefaction Cycles at Elevated Pressure", Master's Thesis, M.I.T. Mechanical Engineering, June 1981
- [SC81] J. H. Schultz, "Preliminary Designs of the FED Cryogenic Refrigeration System for Magnet Cooling at 4.5 and 1.85 K", M.I.T. Plasma Fusion Center Note MITN-81-002, April 1981
- [SM80] J.L. Smith, "Cryogenic Systems: Refrigerators and Liquefiers", M.I.T. Summer Session Course 8.23 Lecture Notes, June 1980
- [ST80] D. Steiner et al., "ETF Interim Design Description Document", ETF Design Center Report, July 1980

Table I

Cryogenic Loads on the FED System
and Helium Coolant Flows

Source	Helium Flow Properties						
	Load (kW)	T_{in} (K)	T_{out} (K)	P_{in} (atm)	P_{out} (atm)	\dot{m} (g/s)	δ (W/K)
TF Winding							
Hot channel	0.018	1.85	3.2	4.0	2.3	5.8	-
Average winding load header-to-header	9.25	1.85	2.3	4.1	2.25	8,700	9,892
TF joints	1.1	2.3	2.35	2.25	2.25	8,700	
TF inner case channels	37.2	5.0	8.2	2.4	2.3	990	6,272
TF + OOP supports outer case channels	46.3	8.56	10.5	2.4	2.3	4,100	5,285
PF Windings	1.2	4.3	4.2	1.07	0.98	59	286
PF Cases	8.0	4.3	4.2	1.07	0.98	390	1,905
Cold-case to shield-radiation	0.12	8.56	10.5	2.4	2.3	10.6	13
Shield to vacuum dewar-radiation	1.81	40	69.5	15.0	9.67	11.7	42
Cold mass supports-conduction	0.02	8.56	10.5	2.4	2.3	-	-
magnet + instrument TF leads	255 kA	2.35	300	2.25	1.0	30.7	881
magnet + instrument PF leads	450 kA	4.2	300	0.98	0.95	54	1,252
Total rate of entropy generation by load							25,828

Table II.

Entropy Inventory - FED Refrigerator

	\dot{s} (kW/K)
1) <u>Heat Exchangers</u>	
HX1	5.3
HX2	1.7
HX3	5.0
HX4	5.3
HX5	3.1
HX6	1.3
HX7	1.6
HX8	3.2
HX9	0.27
HX10	8.27
HX11	0.07
HX12	0.69
HX13	0.83
HX14	3.85
HX15	<u>0.62</u>
Total, heat exchangers	41.1 kW/K
2) <u>J-T Valves</u>	
JT1	0.01
JT2	0.04
JT3	1.78
JT4	10.96
JT5	0.36
JT6	<u>3.50</u>
Total, Joule-Thomson valves	16.7 kW/K

Entropy Inventory - FED Refrigerator

		§ (kW/K)
3)	<u>Expanders</u>	
	EX1	0.67
	EX2	2.49
	EX3	1.88
	EX4	5.34
	EX5	3.07
	EX6	5.91
	EX7	<u>0.86</u>
	Total, Expanders	39.58 kW/K
4)	<u>Compressors</u>	
	C2	0.49
	C3	0.84
	C4	0.93
	C5	1.09
	C6	0.93
	C7	<u>8.18</u>
	Total, compressors, excl. of C1	12.46 kW/K
5)	<u>Mixing</u>	2.61 kW/K
6)	<u>Loads</u>	
	TF Winding	9.89
	TF cases, inner channels	6.27
	TF cases, outer channels	5.29
	PF coils and cases	2.19
	Radiation shield	0.05
	Leads	<u>2.13</u>
		25.83 kW/K
	Total entropy generation, refrigerator	138.3 kW/K

Table III
 Temperatures and Pressures in the
 FED Cryogenic Refrigeration System

Node (See Figure 1)	Temperature (K)	Pressure (atm)
1	305	17.3
2	185	16.3
3	154	9.0
4	154	16.2
5	69.5	8.86
6	68.0	16.0
7	69.5	9.67
8	39	1.3
9	39.7	15.7
10	25	15.64
11	20.2	8.0
12	20.2	15.61
13	12.4	7.92
14	12.4	15.58
15	9.9	15.56
16	7.1	1.42
17	7.5	15.54
18	6.28	15.53
19	8.0	2.5
20	5.14	2.5
21	4.3	1.1
22	6.1	4.25
23	2.4	2.3
24	4.3	1.1
25	4.3	1.1
26	3.76	4.2
27	4.3	1.1
28	8.2	2.4
29	4.2	0.97
30	3.37	4.15
31	2.6	4.1
32	1.85	4.0

Temperatures and Pressures in the FED
Cryogenic Refrigeration System-continued

Node (See Figure 1)	Temperature (K)	Pressure (atm)
33	2.35	2.3
34	2.45	2.25
35	8.5	2.4
36	10.5	2.3
37	8.9	1.4
38	3.9	1.05
39	3.27	0.35
40	3.27	0.35
41	2.5	0.1
42	2.5	0.1
43	1.8	0.016
44	1.8	0.016
45	4.4	0.1
46	8.13	0.35
47	15.8	1.35
48	2.49	0.1
49	4.54	0.35
50	9.13	1.39
51	4.2	0.97
52	4.2	0.97
53	4.6	1.41
54	7.1	1.4
55	9.13	1.39
56	10.8	1.35
57	20	1.33
58	23.4	1.32
59	39	1.29
60	64.9	1.24
61	151.6	1.17
62	178.7	1.14
63	302	1.05

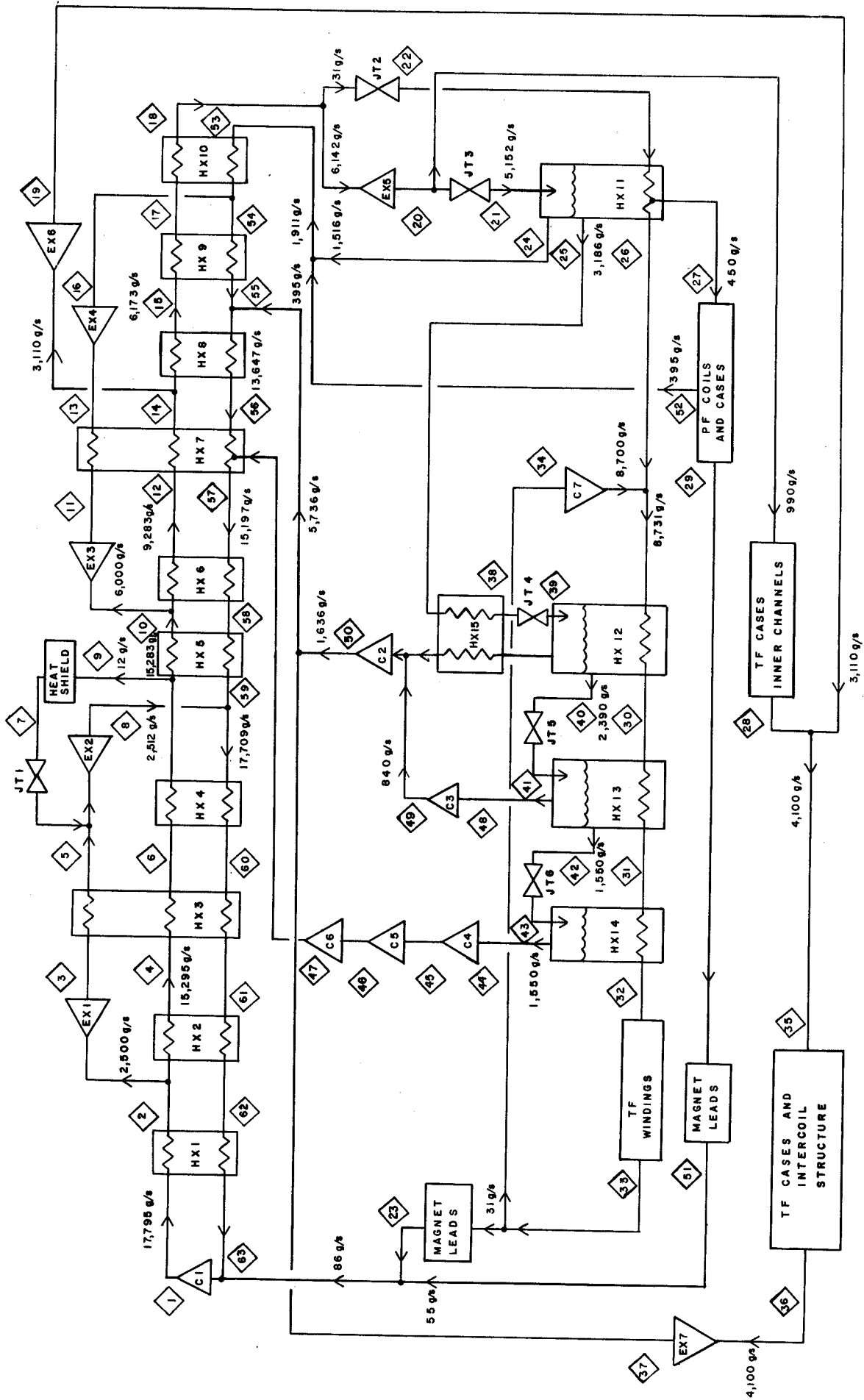


Figure 1.
Line Diagram of the FED Cryogenic Refrigeration System.

EXTERNAL DISTRIBUTION

Institutions

Argonne National Laboratory
Association Euratom-CEA
Grenoble, France
Fontenay-aux-Roses, France
Atomics International
Austin Research Associates
Bank of Tokyo
Brookhaven National Laboratory
CNEN-Italy
College of William and Mary
Columbia University
Cornell University
Laboratory for Plasma Studies
Applied & Engineering Physics
Culham Laboratory
Culham Laboratory/Project JET
E G & G Idaho, Inc.
Electric Power Research Institute
General Atomic Company
General Electric Company
Georgia Institute of Technology
Grumman Aerospace Corporation
Hanform Engineering Development Lab.
Hiroshima University
Japan Atomic Energy Research Institute
Kernforschungsanlage/Julich GmbH
Kyoto University
Kyushu University
Lawrence Berkeley Laboratory
Lawrence Livermore Laboratory
Los Alamos Scientific Laboratory
Max Planck Institut für Plasma Physik
McDonnell Douglas Astronautics Co.
Nagoya University
Naval Research Laboratory
New York University/Courant Institute

Nuclear Service Corporation
Oak Ridge National Laboratory
Osaka University
Physics International Group
Princeton University/Plasma Physics
Sandia Research Laboratories
Science Applications, Inc.
Fusion Energy Development
Lab for Applied Plasma Studies
Plasma Research Institute
Stanford University
University of California/Berkeley
Dept. of Electrical Engineering
Dept. of Physics
University of California/Irvine
University of California/Los Angeles
Dept. of Electrical Engineering
Dept. of Physics
Tokamak Fusion Laboratory
School of Eng. & Applied Science
University of Maryland
Dept. of Electrical Engineering
Dept. of Physics
Inst. for Physical Science & Tech.
University of Michigan
University of Rochester
University of Texas
Dept. of Mechanical Engineering
Dept. of Physics
University of Tokyo
University of Washington
University of Wisconsin
Dept. of Nuclear Engineering
Dept. of Physics
Varian Associates
Westinghouse Electric Corporation
Yale University

EXTERNAL DISTRIBUTION

Individuals

Amheard, N.
Electric Power Research Institute

Balescu, R.C.
University Libre de Bruxelles

Bartosek, V.
Nuclear Res. Inst., Czechoslovakia

Berge, G.
University of Bergen, Norway

Braams, C.M.
FOM/Inst. for Plasma Phys., Netherlands

Brunelli, B.
C.N.E.N.-Centro Frascati, Italy

Brzosko, J.S.
Inst. of Physics, Warsaw University

Cap, F.
Inst. fur Theor. Physik, Innsbruck

Conn, R.W.
Chemical Engineering, UCLA

Consoli, T.
Residence Elysee I, Claud, France

Cuperman, S.
Dept. of Physics, Tel-Aviv University

Engelhardt, W.
Max-Planck Institute für Plasmaphysik

Engelmann, F.
FOM/Inst. for Plasma Phys., Netherlands

Fiedorowicz, H.
Kaliski Inst. of Plasma Physics, Warsaw

Frolow, V.
Div. of Research & Laboratories, Vienna

Fushimi, K.
Science Council of Japan, Tokyo

Gibson, A.
JET/Culham, Abingdon, England

Goedbloed, J.P.
FOM/Inst. for Plasma Phys., Netherlands

Goldenbaum, G.
Lawrence Livermore Laboratories

Hamberger, S.M.
Australian National University

Hellberg, M.A.
University of Natal, South Africa

Hintz, E.A.K.
Kernforschungsanlage/Julich GmbH

Hirose, A.
University of Saskatchewan

Hirsch, R.
EXXON Research & Engineering Co.

Hosking, R.J.
University of Waikato, New Zealand

Ito, H.
Osaka University

Jacquinet, J.G.
CEN/Fontenay-aux-Roses, France

Jensen, V.O.
Riso National Lab, Denmark

Jones, R.
National University of Singapore

Kadomtsev, B.B.
Kurchatov Institute, Moscow

Kostka, P.
Central Res. Inst., Budapest

Kunze, H.-J.
Ruhr-Universität, F. R. Germany

Lackner, K.
Max-Planck Inst. für Plasmaphysik

Lee, S.
University of Malay

Lenhert, B.P.
Royal Inst. of Technology, Sweden

Malo, J.O.
University of Nairobi, Kenya

Mercier, C.H.B.
C.N.E.N./Fontenay-aux-Roses, France

Nodwell, R.A.
University of British Columbia, Canada

Offenberger, A.A.
University of Alberta, Canada

Ortolani, S.
Centro di Studio/C.N.R., Italy

Palumbo, D.
Rue de la Loi, 200, Bruxelles

Pellat, R.
Centre National, Palaiseau, France

Paquette, G.
Universite de Montreal, Canada

Rabinovich, M.S.
Lebedev Institute, Moscow

Razumova, K.A.
Kurchatov Institute, Moscow

Register, A.
Kernforschungsanlage/Julich GmbH

Rosenau, P.
Technion, Haifa, Israel

Rosenblum, M.
Soreq Research Center, Yavne, Israel

Rudakov, L.I.
Kurchatov Institute, Moscow

Ryutov, D.D.
Nuclear Physics Instit., Novosibirsk

Salas, J.S.R.
Inst. Nacional de Investig. Nucleares

Shafranov, V.D.
Kurchatov Institute, Moscow

Smirnov, V.P.
Kurchatov Institute, Moscow

Spalding, J.-J.
Culham Laboratory, Abingdon, England

Tachon, J.
CEN/Fontenay-aux-Roses, France

Tewari, D.D.
Dept. of Physics, IIT, New Dehli

Trocheris, M.
CEN/Fontenay-aux-Roses, France

Vandenplas, P.E.
Ecole Royale Militaire, Bruxelles

Verheest, F.
Rijksuniversiteit, Gent, Belgium

Watson-Munro, C.N.
University of Sydney, Australia

Wesson, J.A.
Culham Laboratory, Abingdon, England

Wilhelm, R.
Inst. für Plasmaphysik, Stuttgart

Wilhelmsson, K.H.B.
Chalmers Univ. of Technology, Sweden

Wobig, H.
Max-Planck Inst. für Plasmaphysik