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ENGINEERING AND MANAGEMENT ASPECTS OF THE ORMAK PROGRAM

M. Roberts

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Oak Ridge, Tennessee 37830

I. Introduction

A. Purpose

This paper has two major objectives. The first of these is to lay the groundwork for succeeding ORMAK related papers in these proceedings. The second is to make clear the general work environment in terms both of the resources and the management requirements of the ORMAK program.

B. Historical Background

The ORMAK program was conceived in early 1969 as a two-phased project in which a conservative match to the Russian TM-3 device geometry would first be made and then second, an attempt at a lower aspect ratio, larger bore version, in which hot ions could be produced, would be made. In 1970, the direction of the program was changed to one aimed directly at the production of a low aspect ratio, moderate field, large bore, hot-ion device which is the present ORMAK facility. Later that year, recognition of the potential usefulness of neutral beam injection heating led to a further evolution of the program into one stressing both confinement and heating. The completion of the ORMAK device occurred in early 1971 and after a number of months of testing and debugging, plasma operations began. Machine operation,[1] plasma production, and diagnostics all were improved throughout 1972 and basic tokamak physics experiments[2] were conducted during 1973 along with injection heating experiments which began in mid-1973.

II. Engineering

A. ORMAK (and ORMAK related) Program Elements – Purpose and Present Work

1. ORMAK Operations (Operations Group within ORMAK Section). The basic engineering thrust of this element is to improve continuously machine operation and diagnostic capabilities carrying on a large number of widely differing and usually independent tasks. Crucial problems detected early in the experimental operation have, by and large, been corrected during those first two years of operation. We are presently at a point of improving those systems which still can hamper reliable operation or impede rapid data acquisition.[3] These jobs include various disciplines of engineering from electronics to electrical engineering to mechanical engineering, cryogenics and vacuum considerations.[4,5] In terms of function, these jobs range from improving the range of the OH power supply and making it modular, to installing a subcooler on the liquid-nitrogen coolant system for increased TF coil thermal capacity, to the general aim of extending the coverage of many diagnostics[6,7] from single point measurement to multipoint profiles to two-dimensional

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have been noted, analyzed, and are being eliminated. The present and near term work is associated with the removal of the remaining flaws from the present design and investigating improved ways of dealing with the system. These present mechanisms are within the vacuum topology of the outer vacuum system but are designed to be outside the machine's thermal island at 80K. It is believed that, for the long term, an improved system would result from changing the vacuum topology so that the mechanisms are removed from within the vacuum and thermal enclosures.

3. High Field ORMAK (Planning and Engineering Group within ORMAK Section). The basic idea of the High Field ORMAK modification is to permit a doubling of the plasma current, which will enable us to generate an increasingly hot and increasingly collisionless plasma. The plasma current doubling can be achieved by doubling both the toroidal field and the volt-second capability of the central core. There are two parts to the work in the main. One part is the design, procurement, fabrication, and assembly of a 100-MVA power system that will generate the doubled magnetic field from a solid-state rectifier system. The other part is the set of modifications to the toroidal field coil system and other parts of the internals of the machine associated with doubling the field, e.g., OH core, and OH coil supports.

The power system provides transformation for the 1-sec, 100-MVA pulse from the 161-kilovolt level down to the one-thousand-volt level for the solid-state rectifier systems, control of the power in the full-wave, multi-phase bridge rectifier, and then transmission to the present ORMAK device. Within the machine itself the toroidal field coils, although similar to present ones, are being upgraded in terms of mechanical strength and electrical insulation so that they can withstand repeatedly the quadrupled forces. Similarly the ohmic heating core has to be doubled to provide the volt-second change necessary at the higher magnetic fields and the ohmic heating and vertical field coil systems must also be strengthened to support the quadrupled forces.

4. ORMAK-F/BX (Planning and Engineering Group within ORMAK Section). This element of the ORMAK program is concerned with preparations for a large, future experiment dealing with fusion feasibility and D-T burning. One of the basic concepts is the ability to use the same facility for both the hydrogen and the D-T experiments with a minimum of change between the two. At present, a conceptual design study[8] is being conducted to identify the problems and to develop a self-consistent picture of the entire facility including physics knowns and unknowns relevant to the design, personnel requirements, technological development requirements, and design engineering requirements. The facility description and its requirements will be translated into costs to provide AEC-DCTR with useful planning information for its decision making process.

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2. Injection (Planning and Engineering Group within ORMAK Section). This program element is concerned principally with the adaptation of ion sources to the plasma system and is therefore basically a mechanical, electrical, and vacuum engineering job of connections, alignments, and gas handling.[8] Two injector systems have been in operation on the ORMAK device for a number of months. Some operating defects

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5. Neutral Beam Development (Energetic Particle Injection Group). This area of injection heating technology is being pursued in order to increase the neutral beam source strength and usefulness for increased heating experiments in the near future. The work being conducted now has two parts: one dealing with the development of the source itself[10] aiming in the near future for a doubling of the source strength either by focussing in which the beam intensity would increase or simply by enlarging the size in which case the beam

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power would increase. Additionally, work is aimed toward adapting a given laboratory source for field installation.[11]

6. Magnet Development (Engineering Science Group) There are two specific aims in the ORMAK magnet development work. The first is the development of various possible types of cryogenically cooled copper coils for use at centerline fields up to 50 KG in High Field ORMAK.[12,13,14] The second is the development program aimed toward successful design of large 5-6m bore ORMAK F/BX coils using superconducting materials. In the High Field ORMAK case, the development centers about the insulation problems encountered at high intensity low temperature, pulsed coil conditions and the necessary potting that goes along to protect that insulation. In the F/BX case the work is being conducted by identifying the detailed steps in the development program and by preparing for conductor configuration selection and qualification tests.

7. Liner Surface Development (Engineering Science and Operations Groups). The basic requirement in this area is the production of the least obtrusive surface for use with high energy plasma particles. At present the work is focussing on the selection of particular metals or perhaps carbides for use as a possible liner surface. We are looking at those materials that have low sputtering yields and low Z's in order to produce the most benign surface in regard to plasma contamination from wall bombardment.

B. Description of the Present ORMAK Facility (Design Objectives, Implementation and Tasks)

The basic design of low aspect ratio, moderate magnetic field and long experiment time was devised to produce the most reactor-like physics, specifically in terms of the orbits-per-collision measure. Although each element in the design is presented as a design objective, it is only through the particular combination of elements that the physics goal can be reached and, concomitantly, that the engineering problems become severe.

1. The Design Objective of Low-Aspect Ratio requires high current densities in the various windings and minimum clearances for all parts of the device. For short pulses, high current densities are most effectively achieved at cryogenic temperatures, the combination of which implies high differential temperatures across long conductors. The compactness of low aspect ratio means that the thermal insulation has to be done with the minimum size dewar, or no dewar preferably, which then involves a large, all enclosing vacuum system. The problems that one encounters in this method of implementation are those associated with liquid-nitrogen temperature usage and vacuum enclosures and especially, and most persuasively, the reliability questions exacerbated by small clearances and the close packing in a toroidal system. (With future, larger systems, some of the difficulty associated with the scale size of "small" clearances should be lessened.) In particular, one must deal with a multitude of liquid-nitrogen temperature, vacuum

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rectifier systems. The problems accompanying the magnetic field have to do with the mechanical, electrical, and thermal problems associated with both the tens-of-megawatts power handling and the more than 10-MJ energy storage.

To support the nominal 25 kG center field which produces a strong radial inward force of 500 tons, a multi-part structural system was developed which includes at its center a thin, annular, bucking ring against which each of the 56 toroidal field coils presses. The coil mounts are held at the top and bot-and are keyed on the bucking ring by fiberglass plates recessed into slots. In addition to the mechanical forces on the toroidal field coils themselves, the more difficult problem arises from the interaction of the current in the (poloidally directed parts of the) ohmic heating and vertical field windings with the toroidal field. These windings are enclosed in tight quarters permitting rather small support structures upon which and by which they can be fastened.

In terms of electrical engineering, a central problem has been that of wave shaping of the long time-constant, steady-state generator outputs for the particular job at hand. We have used solid-state regulators to drive the generators' field windings first with high voltage in one direction and then with high voltage in the other direction as we ramp the current up as fast as possible before maintaining a flat top. Protection from conditions arising from faults in either the load or the generators is provided by a set of four large circuit breakers which are actuated on each pulse to connect the rotating machinery at full energization to the load and then remove it after the field is removed at the end of the pulse.

In terms of the thermal problems, one must consider the thermal inertia in the generators and in the coils and make sure that the overall experiment time is kept to an absolute minimum, the actual usable flat field time is small compared to the overall experiment time. Associated with the thermal inertia is the heat removal problem whose characteristics of copper-to-coolant heat transfer, coolant circulation, and coolant-coolant heat exchange determine the pulse repetition rate allowable.

3. The Design Objective of Long Experiment Time is necessary to allow us to observe and measure plasma characteristics over a period that is at least equal to one, or, preferably, more periods of equilibration between the plasma temperature and the injected beam input. For long experiment time, it is necessary to maximize the power transfer into the load's given thermal inertia and also to maximize the ohmic heating flux change. The problems that are encountered with this scheme of implementation are based on the fact that one faces the temperature limit in the copper coils. This limit is actually the temperature limitation of the liquid-nitrogen coolant because with so many paths and so many feet per path, it is impractical to purge the lines of the coolant before each shot. Therefore one uses pressurized liquid nitrogen so that the coolant will remain in a single phase condition, but, if the temperature were to rise continuously, then at some point all the liquid nitrogen would vapor-

low temperature, pulsed coil conditions and the necessary potting that goes along to protect that insulation. In the F/BX case the work is being conducted by identifying the detailed steps in the development program and by preparing for conductor configuration selection and qualification tests.

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2. The Design Objective of a Moderate Magnetic Field (25 KG) has required some tens of megawatts power delivery from four steady-state DC machines. With the change to High Field ORMAK, this tens-of-megawatts requirement will increase to nearly a hundred MVA but will be supplied from four solid-state

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In terms of electrical engineering, a central problem has been that of wave shaping of the long time-constant, steady-state generator outputs for the particular job at hand. We have used solid-state regulators to drive the generators' field windings first with high voltage in one direction and then with high voltage in the other direction as we ramp the current up as fast as possible before maintaining a flat top. Protection from conditions arising from faults in either the load or the generators is provided by a set of four large circuit breakers which are actuated on each pulse to connect the rotating machinery at full energization to the load and then remove it after the field is removed at the end of the pulse.

In terms of the thermal problems, one must consider the thermal inertia in the generators and in the coils and make sure that the overall experiment time is kept to an absolute minimum; the actual usable flat field time is small compared to the overall experiment time. Associated with the thermal inertia is the heat removal problem whose characteristics of copper-to-coolant heat transfer, coolant circulation, and coolant-coolant heat exchange determine the pulse repetition rate allowable.

3. The Design Objective of Long Experiment Time is necessary to allow us to observe and measure plasma characteristics over a period that is at least equal to one, or, preferably, more periods of equilibration between the plasma temperature and the injected beam input. For long experiment time, it is necessary to maximize the power transfer into the load's given thermal inertia and also to maximize the ohmic heating flux change. The problems that are encountered with this scheme of implementation are based on the fact that one faces the temperature limit in the copper coils. This limit is actually the temperature limitation of the liquid-nitrogen coolant because with so many paths and so many feet per path, it is impractical to purge the lines of the coolant before each shot. Therefore one uses pressurized liquid nitrogen so that the coolant will remain in a single phase condition, but, if the temperature were to rise continuously, then at some point all the liquid nitrogen would vaporize and a large pressure would be encountered in the lines. In order to stay below this critical point, one has to keep the coolant temperature below 126K. This temperature limit puts a premium on the highest voltage, highest power transfer possible to allow a given experimental time with a minimum of joule heating before and after that time. In addition to the temperature limitation, the area available in the center of the bucking ring for a ferro-magnetic core is limited. This means that the highest quality (especially saturation field strength at reasonable permeability) ferro-magnetic material must be used with the

highest packing factor and with the use of negative flux biasing to achieve the greatest amount of flux change.

4. The Design Objective of Programmable Plasma Current and Vertical Field has been felt by us to be important since the first days of sharing the Russian tokamak experience. One of the few (and as it turns out one of the critical) experimental controls in the tokamak device is control of the strength and timing of the vertical field as well as of the ohmic heating current. Because of the criticality of these two wave shapes, we instituted the use of transistor controlled battery supplies for the production of both these currents (magnetic fields). Although straightforward in concept the reliable use and protection of large scale transistor battery supplies has proven to be a considerable undertaking.

5. The Design Objective of High Plasma Purity has only been recognized as being critical in the last year or so. The implications on the engineering requirements for this objective has now become clear — that is, one requires a liner system that is more bakeable, more tight, and more clean than originally required.[15] The present 150°C–200°C bake is being extended to all parts of the liner system and the baking temperature is being increased to 400–500°C in next generation liners. The leak rate between the inner and outer vacuum of the liner is now 1ℓ/sec as opposed to the original achievement of 10ℓ/sec. The cleanliness or base pressure is being improved from the present 10^{-7} torr to the 10^{-8} to 10^{-9} range. The problems that are encountered are ones associated with high-vacuum achievements in large, field systems as distinct from large, laboratory systems, i.e., in relatively less controlled physical and support personnel environments (field) rather than more (laboratory). This distinction has to do with both cleanliness, standards, and personnel procedures. One must be prepared to deal with surface preparation, surface coating, various kinds of turbomolecular pumping and the thermal expansions resulting from a temperature differential in the liner surface as large as 700 degrees centigrade. This large differential temperature expansion requires rather strict accounting of all the attachments onto the liner and how they affect the overall liner support and each other.[16]

6. The Design Objective of Diagnostic Access is, in ORMAK as it is in other devices, the achievement of many entrances into the plasma, each of which is to be made with ease and reliability. The problems that stand in the way of this easy, multiple access are at least two. First, for best plasma behavior, the magnetic field coils are arranged in a two-dimensional matrix around the plasma surface limiting the size of any given typical access to a small square. Second, the necessity for a double vacuum system, with the liner being the inner system and the large vacuum tank being the outer system, requires a set of double seals at each point thereby reducing the number of accesses that can be made for a given cost.

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Figure 1 illustrates an overall view of the ORMAK system without the injectors on. Figure 2 illustrates much the same view but in sketch form with major components labelled, and Fig. 3 illustrates the same system with the tank off showing more clearly the various parts alluded to in the text.

III. Management

The ORMAK Section is but a large fraction of the Thermonuclear Division which is one of about twenty divisions in the Oak Ridge National Laboratory which, itself, is one of four major installations operated for the USAEC by the Nuclear Division of Union Carbide Corporation.

A. ORMAK as Part of the General Fusion Effort

As the ORMAK program includes many of the elements typical of the overall CTR program today, we find, in one system and in one location, many of the effects of the overall transition in fusion from a small physics and engineering program to a much larger and more engineering oriented, physics and engineering program. As a result of being in the transition between small and large, it is now appropriate and necessary for us to institute on a more consistent basis the various techniques of professional management that are recognized and now available. In a circumstance fortuitous for us, the Union Carbide Corporation has in the last year instituted the practice of a pervasive management system which is based upon the ideas of professionalism and usefulness in management techniques. These techniques reinforce the positive parts of the actions that we have been taking and give guidance where our efforts have been less than adequate. The experimental fusion systems are sufficiently large that it is no longer possible for a single leader to be personally aware on a daily basis of all the activities of the various groups. Therefore a consistent reporting scheme and controlling scheme must be instituted and since it is a long-range, long-term effort, personnel as well as procedures must be developed. As an example, a year and a half ago, we began to apply the existing UCCND accounting scheme whereby each particular job is separately accounted and its actual cost compared with an estimate in the various phases of a job whether it be design or procurement, fabrication or operation. This scheme has allowed for development of the ORMAK budget in its many elements and now provides the base each year for informed preparation of the budget.

B. ORMAK in the Oak Ridge System

The ORMAK program does not stand as an entity unto itself in the Oak Ridge complex but rather is one growing part of a rather large system. "Large" here is typified by the engineering phases of the system which are currently involved in projects that are orders of magnitude larger than current fusion efforts and are associated with the gaseous diffusion plant expansion. Therefore, in order to be successful, we must make our requirements known as explicitly and as early as possible to the management of the larger system so that we might have our personnel

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7. The Design Objective of Injection Heating Capability is instituted to provide a proof of an adequate means of raising the ion temperature to that required for thermonuclear reactors. In the 56-fold ORMAK symmetry, local distortion of a number of coils is required to produce a sufficiently large tangential access. The problems associated with the injection system have been two: first, we have the beam line requirements which form the basis for adaptation between the source and the plasma. These gas handling and alignment requirements have to be met by various valving, pumping, and structural systems in a restricted area. Second, the perturbed coils must be

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As examples of the resources required and used to date, our engineering assistance has been received from various areas of the Union Carbide Nuclear Division complex including staff from the Thermonuclear Division, various other parts of the Oak Ridge National Laboratory, the consolidated Union Carbide Engineering Services, Architect-Engineering firms and also consultants. The participation of these personnel has extended to all areas of engineering, including mechanical, electrical, cryogenic, vacuum, structural, safety and remote handling topics.

Similarly, personnel from these various internal organizations as well as industrial concerns have been involved with many development efforts in their particular specialties, namely coil and coil systems, liner surface preparations, injection source and source adaptations.

In terms of fabrication, nearly all the major pieces of the ORMAK system as well as many of the smaller parts were fabricated in-house. This choice was made basically because of the time pressure to achieve completion on these items. Of the significant parts, only the ferromagnetic core and the rolling of the cylindrical part of the vacuum tank were done outside the Union Carbide Nuclear Division complex. As our needs grow, we are becoming involved more and more with industrial participation in accordance with AEC policy.

C. Present ORMAK Organizational and Management Structure

Within the Thermonuclear Division, the ORMAK Section Leader and various Group Leaders (for Energetic Particle Injection, Engineering Sciences, etc.) report directly to the Division Director. Within the ORMAK Section there are three groups — Operations, Physics, and Planning and Engineering. Engineering activities other than of an operating nature are included with the purview of this third ORMAK group. As examples of project management, one can examine the High Field ORMAK and ORMAK F/BX program elements as defined earlier. In each case, there is a Program Manager with technical and managerial responsibility who reports directly to the Group Leader. A design review committee composed of the ORMAK Section management reviews and approves each major design criterion in a documented fashion including wide participation in the Division. Internal advisory committees review the progress of each project with Division management on a monthly basis and an AEC-DCTR review is conducted on each project at various times during the projects's course. In addition to these programmatic review processes, there are also other systematic reviews associated with Quality Assurance, Safety, and Fiscal Control.

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1. W. Halchin et al., "O
Fourth Symposium on E
Research, Washington,
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2. ORMAK Staff, "The Sta
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3. J. E. Francis et al.,

4. W. Halchin et al., Ope
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of the DuoPIGatron Ion

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References

1. W. Halchin et al., "ORMAK Facility," Proceedings Fourth Symposium on Engineering Problems of Fusion Research, Washington, D.C., NS-18 No. 4, April 20-23, 1971
2. ORMAK Staff, "The Status of the ORMAK Experiment," Proceedings, Third Int'l Symp. on Toroidal Plasma Confinement, Garching, March 1973.

The remaining references (3-16) are all papers that were given at the Fifth Symposium on Engineering Problems of Fusion Research, Princeton, N. J., Nov. 6-9, 1973.

3. J. E. Francis et al., "ORMAK Data Handling."
4. W. Halchin et al., Operation of the ORMAK Experimental Fusion Device in a Cryogenic, Vacuum Environment."
5. H. M. Long and J. N. Luton, Jr., "Cryogenic Engineering for ORMAK."
6. J. S. Culver and M. Murakami, "Mechanical and Optical Coupling of a Thomson Scattering Laser to Measurement to the ORMAK Machine."
7. C. R. Dyer and M. Murakami, "A Low-Noise Data Collection System for the Thomson Scattering Diagnostic Apparatus on ORMAK."
8. D. C. Lousteau et al., "Mechanical Interfacing the High Power Neutral Injector on Heaters to ORMAK."
9. P. N. Haubenreich et al., "Conceptual Design Study for the ORMAK F/BX Facility."
10. R. C. Davis et al., "Engineering Considerations of the DuoPIGatron Ion Source."
11. L. D. Stewart et al., "Design of High Power Neutral Injection Heaters for the ORMAK System."
12. W. F. Gauster et al., "Analysis of the 50 kG Toroidal Field Coil for High Field ORMAK."
13. J. N. Luton, Jr. et al., Development of the 50 kG Toroidal Field Coil for High Field ORMAK."
14. R. W. Derby, "On the Influence of the Between-the-Turns Thermal Insulation on the Duty Cycle of a Large, Pulsed Coil for Use on ORMAK and High Field ORMAK."
15. J. E. Simpkins, "Passivation of the ORMAK Vacuum Liner."
16. S. M. DeCamp et al., "Development, Fabrication and Assembly of a Thin Wall, Low Aspect Ratio Liner and the Enclosed Tungsten Limiter for ORMAK."

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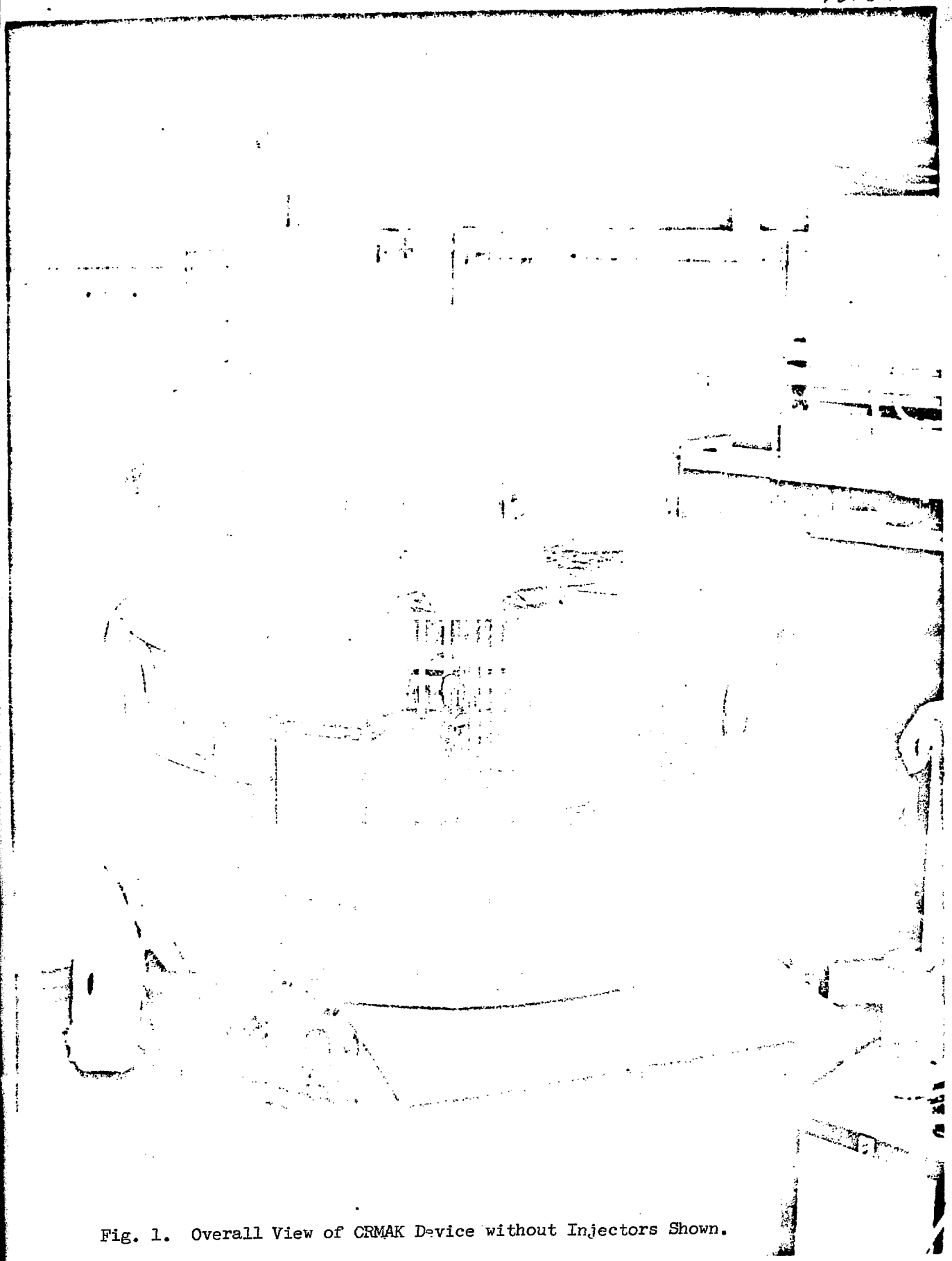
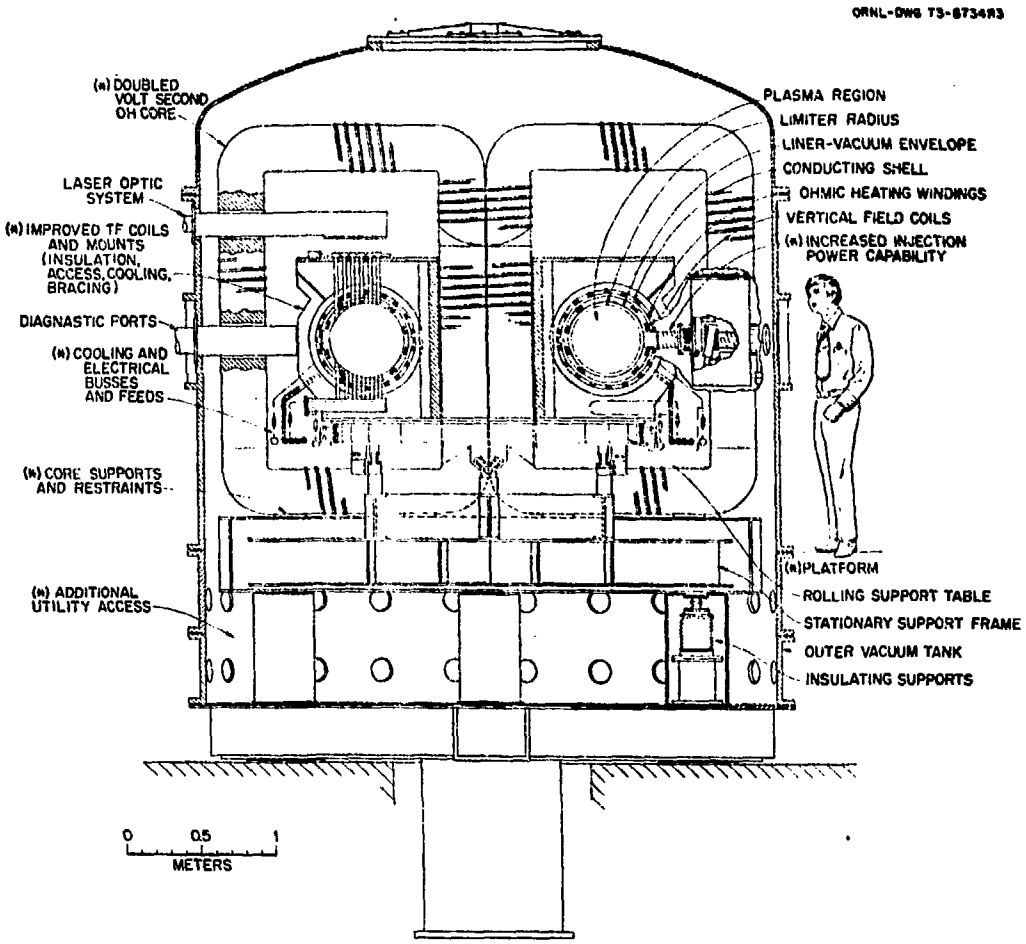


Fig. 1. Overall View of CRMAK Device without Injectors Shown.



Cross Section of High-Field ORMAK
Device with Major Modifications Indicated by Asterisks (*)

Fig. 2

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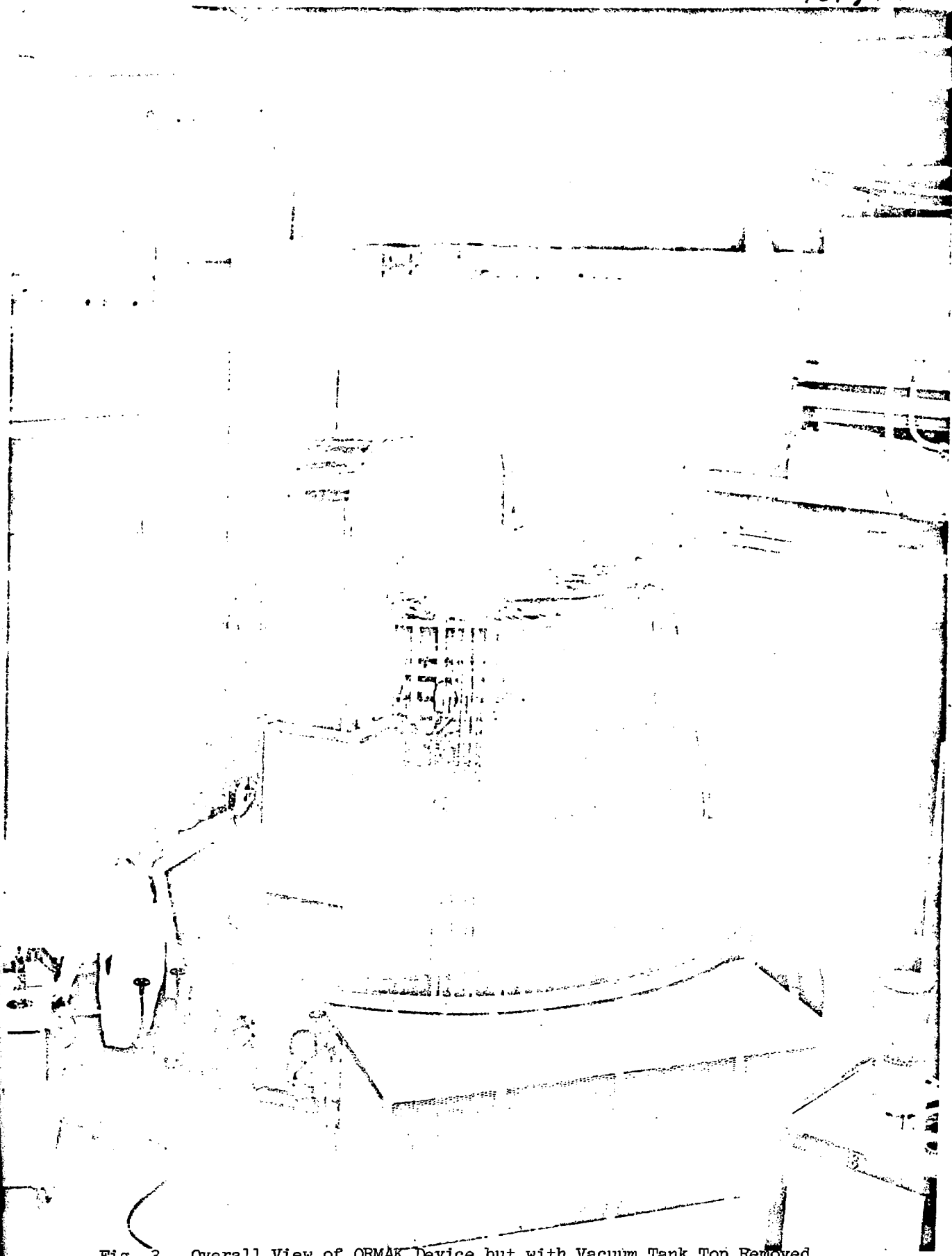

Fig. 3. Overall View of ORMAK Device but with Vacuum Tank Top Removed.