CONTENTS

6.0 RELIABILITY, AVAILABILITY, AND MAINTAINABILITY ASSESSMENT

6.1 INTRODUCTION

This section describes the reliability, availability, and maintainability (RAM) assessments performed on the SOMBRERO and Osiris reactor plants. The primary objectives are to assess the RAM aspects of the two designs and to establish availability goals for the major plant systems to aid in planning future development efforts.

6.2 AVAILABILITY ASSESSMENT

6.2.1 Approach and Methodology

The SOMBRERO and Osiris power plant designs are not detailed enough to estimate plant availability with any confidence. The approach, therefore, is to first make a rough estimate of the availability of the plant subsystems and then to use these estimates to establish availability goals for the major plant systems that combine to the give the desired availability goal for the entire plant. The initial estimates are in essence weighting factors for allocating system availability goals.

For RAM assessment purposes, each reactor plant is partitioned into four major systems: driver, reactor, target (fabrication, injection, and tracking), and energy conversion/balance-of-plant. In assessing the availability, each major system is divided further into several functional subsystems, and an achievable availability is estimated for each subsystem. The estimated availability is determined based on existing similar systems or comparable systems taking into account expected component lifetime, equipment random failure rate, power output fractions, manufacturing process capacity factor, and in-process storage capacity. For systems in which RAM data are nonexistent, the estimated availability is projected with the consideration of the complexity and technology risk associated with the system: a projected availability of 0.9 for systems of high complexity, 0.99 for systems of moderate complexity, and 0.999 for systems of low complexity.

Based on the estimated subsystem availability, the overall plant availability goal is apportioned to individual subsystems according to a model described in Ref. 6.1. The availability goal for each subsystem is:

$$A_i = (A_{goal})^{w_i}$$

where

A_{goal} = availability goal for plant,

w_i = $\ln(A_s) / \ln(A_p)$ = weight factor for the i-th subsystem,

A_p	=	estimated availability for power plant, and
A_s	=	estimated availability for i-th subsystem.

6.2.2 Plant Availability Goal

The plant availability is defined as the actual annual MWh output divided by the potential annual MWh output of the plant. An overall plant availability goal of 75% is assumed for the IFE reactor plants so as to be comparable to other fusion reactor studies and current large electric power generating systems (e.g., the conventional nuclear power systems, which are operating with an availability of 60 to 80%, and up to 90% for CANDU reactors, which have on-line refueling). To achieve this goal, the required effective operation availability is 81% after allowing for an assumed downtime of four weeks each year to account for preventive maintenance activities.

6.2.3 Systems Availability Allocations

Preliminary estimates indicate that the availability of the SOMBRERO power plant is 0.68, and the availability of the Osiris power plant is 0.70. The high reliability of the KrF driver is due mainly to spare amplifiers (64 provided while 60 normally used). The estimated availability values for the major SOMBRERO and Osiris systems and subsystems are summarized in Tables 6.1 and 6.2, respectively.

Availability allocation is apportioned for plant systems from the top down according to the reliability and maintainability characteristics of the systems in such a way as to achieve the plant availability goal. The availability apportionment indicates the optimum balance of availabilities for all systems in the plant. The allocation process serves as a means of assessing the design and defines availability improvement targets in system design refinement. These improvements include better system design, application of redundancy, changes in maintenance concepts, or combination of these options.

Using an effective operation availability goal of 81% for the IFE reactor system and the estimated system availability values in the above section, the availability goals for various SOMBRERO and Osiris plant systems are established as indicated in Table 6.3. Comparing these goals to the rough estimates given in Tables 6.1 and 6.2 indicates that for both plants, 4-5% improvements are needed for the drivers, reactors, and target systems, and a 2% improvement is required for the BOP availability in order to meet the overall plant availability goal. However, since RAM data for these systems are mostly nonexistent, or at best available from limited experimental results, these results should not be considered conclusive. More definitive assessments will require detailed designs and evaluations of the plant systems, additional data obtained from extended test periods, and eventually the integration of driver, target, reactor, and BOP systems in an experimental test facility.

Table 6.1. Estimated Availability for SOMBRERO Plant Systems

System	Complexity Rating	Estimated Availability	Based on
Driver Systems		**0.8877**	
Front End Waveform Generation	Low	0.9990	System complexity
Intermediate Amplifying	Moderate	0.9900	System complexity
Final Amplifying	High	0.9985	Estimated MTTR
Optical Compression & Final Focus	High	0.8989	Estimated MTTR
Reactor Systems		**0.8896**	
Reactor Vacuum Vessel	Moderate	0.9620	Estimated MTBF, MTTR
First Wall and Blankets	Moderate	0.9360	Estimated MTBF, MTTR
Fluidized Bed Transport	Low	0.9960	Conventional system
Vacuum	Low	0.9920	Estimated MTBF, MTTR
Target Systems		**0.8991**	
Target Injection	High	0.9000	System complexity
Target Cryogenics	Low	0.9990	System complexity
Tritium Recovery	Low	1.0000	Assumed storage
Target Manufacture	Moderate	1.0000	Assumed capacity
Energy Conversion & BOP Systems		**0.9604**	
Heat Exchange Loop	Moderate	0.9730	Estimated MTBF, MTTR
Turbines	Low	0.9900	Conventional system
Heat Recovery and Rejection	Low	0.9990	Conventional system
Electrical Equipment	Low	0.9990	Conventional system
Instrumentation and Controls	Low	0.9990	Conventional system
Overall Power Plant		**0.6819**	

Table 6.2. Estimated Availability for Osiris Plant Systems

System	Complexity Rating	Estimated Availability	Based on
Driver Systems		**0.8733**	
Ion Injector	Moderate	0.990	System complexity
Induction Linac and PFN	High	0.900	System complexity
Beam Combiner & Final Focusing	Moderate	0.990	System complexity
Vacuum and S.C. Cooling	Moderate	0.990	System complexity
Reactor Systems		**0.9211**	
Reactor Vacuum Vessel	Moderate	0.962	Estimated MTBF, MTTR
First Wall and Blankets	Moderate	0.973	Estimated MTBF, MTTR
Flibe Transport	Low	0.992	Estimated MTBF, MTTR
Vacuum	Low	0.992	Estimated MTBF, MTTR
Target Systems		**0.8991**	
Target Injection	High	0.900	System complexity
Target Cryogenics	Low	0.999	System complexity
Tritium Recovery	Low	1.000	Assumed storage
Target Manufacture	Moderate	1.000	Assumed capacity
Energy Conversion & BOP Systems		**0.9604**	
Heat Exchange Loop	Moderate	0.973	Estimated MTBF, MTTR
Turbine	Low	0.990	Conventional system
Heat Recovery and Rejection	Low	0.999	Conventional system
Electrical Equipment	Low	0.999	Conventional system
Instrumentation and Controls	Low	0.999	Conventional system
Overall Power Plant		**0.6946**	

Table 6.3. Allocated Availability Goals for SOMBRERO and Osiris

	Allocated Availability Goals	
Systems	**SOMBRERO**	**Osiris**
Driver	0.94	0.93
Reactor	0.94	0.95
Target	0.94	0.94
BOP	0.98	0.98

6.3. MAINTAINABILITY OF THE OSIRIS PLANT

In an effort to develop an approach for remote maintenance of the Osiris reactor, an analysis was performed on the sequence and type of activities required in order to remove and replace the Osiris vacuum cover, fabric blanket assemblies, and the maintenance of other reactor support equipment. This analysis resulted in the definition of "theaters" and "classes" of operations. Theaters of operation are defined by geometric constraints which are primarily driven by available access points, and classes of operation are defined by the physical constraints of payload (weights of components to be removed/replaced) and available work envelope (dictated by plausible reach limits of remote handling (RH) equipment and available work space within the internals of the reactors which might impose joint singularity concerns). For the purposes of this study, the theaters of operation are defined as follows:

- Reactor Building / Reactor Top-Hat Area
- Driver Seal Flange Area
- Reactor Internals
- Hot Cell and Maintenance Area.

The theaters of operation were then cross-compiled with the identified activities required for equipment maintenance, removal, and/or replacement. An evaluation of the activities was performed to define the classes of operations that would be conducted. The class of operation is typically characterized by the size and weight range of the components that need to be handled from each of the access points and by the available work envelope in which to conduct the RH system-supported operation. The basic functional specifications for the RH equipment are normally developed from this information. However, due to the conceptual nature of the IFE reactor designs, it would be premature to try to detail discreet specifications for the RH equipment. In an effort to determine a baseline case for overall RH equipment operational envelopes and equipment and component handling sequences (for maintenance activities), the activities that define the classes of operation for the Osiris reactor design are as follows:

- High and Low Pressure Flibe Inlet Pipe Disconnect
- Driver Seal Flange Unbolting and Retraction
- Vacuum Chamber Cover Unfastening and Interference Removal
- Vacuum Chamber Cover and Attached Internals Removal
- Reinstallation.

The Osiris reactor building size is dictated by the maintenance handling requirements for the vacuum vessel cover and reactor internals. These requirements are due to the complexity of refurbishment operations associated with these components and constraints which dictate that the cover and internals be removed as one piece. The physical size of these components and the complexity of refurbishment operations suggest that it is prudent to "replace in kind" rather than "refurbish in place." With this in mind, it is apparent that the remote handling equipment needs to have common access to both the reactor building and the hot cell/maintenance areas. To accommodate this requirement, a large movable shield wall is provided. This shield wall is located between the reactor building and hot cell. The crane bay containing all of the overhead-operated remote handling equipment is open to both (Figs. 6.1 and 6.2). The remote handling equipment is protected from neutron activation during reactor operation by extending the shield wall in place and locating the equipment at the far end of the hot-cell facility. The hot cell contains both a clean room in which to store the new replacement cover and reactor internals (thus isolating them from the old contaminated internals being removed) and a hot storage area, which is a large temporary containment that houses the old components being removed.

The range of tasks required to be performed by the remote handling equipment is not trivial. It is quite apparent that the majority of the tasks to be performed will require significant coordination and the probable use of hybrid systems (in which there will be the use of relatively simple high payload capacity rigid or semi-rigid manipulators/crane system in conjunction with a highly dexterous, force-reflective manipulator system, and special tooling). In addition, great attention to detail will need to be paid to the logistics of component and equipment handling and maintenance requirements. Each of these things will have the potential for significant impact on the overall design of these facilities.

It is worthy to note that design impact and integration considerations of automated systems, advanced work systems (robotics), and remote handling equipment at the conceptual design stage of a project is something of a novel practice. Retrofit operations are extremely

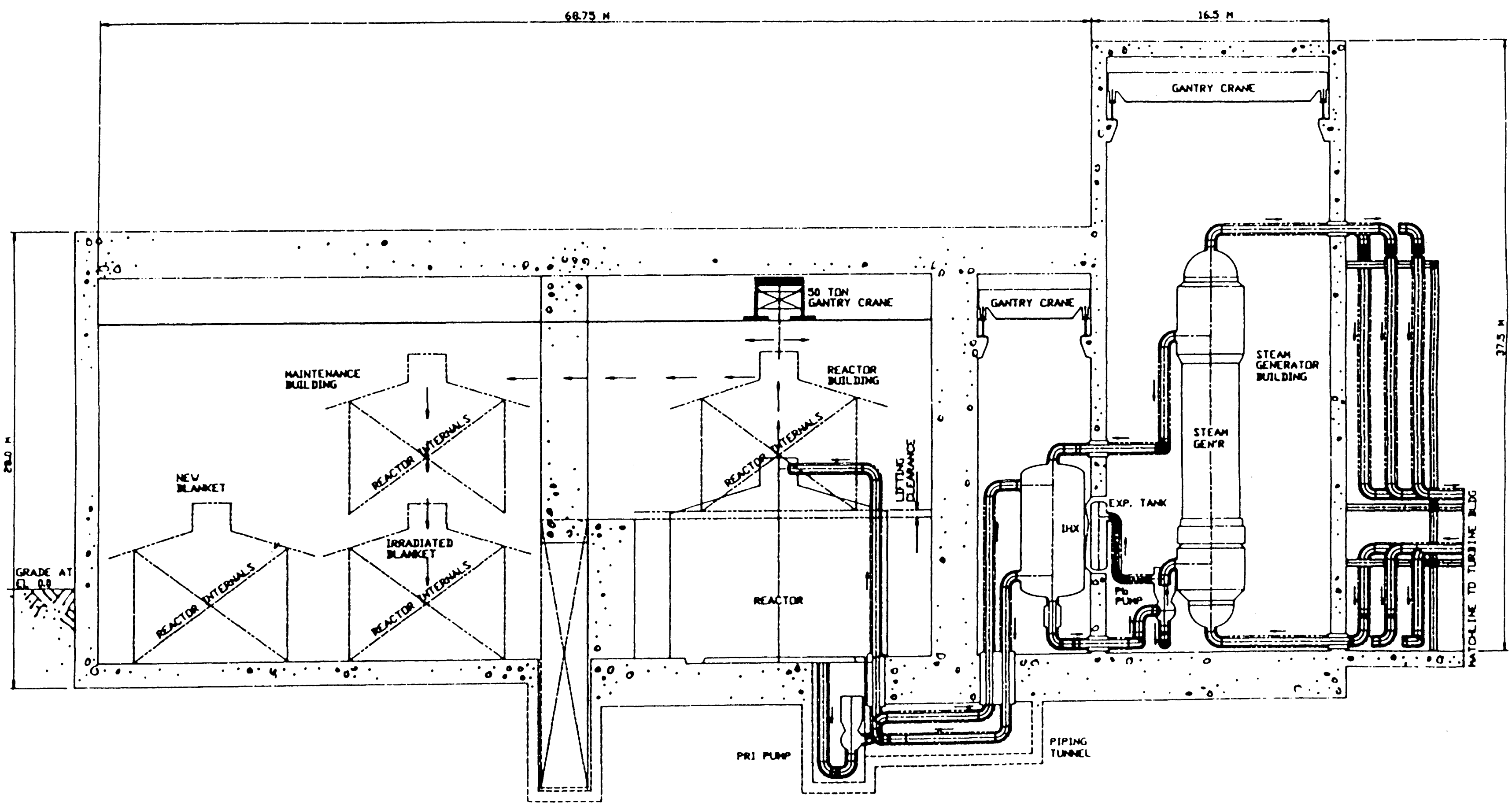

Fig. 6.1. Cross section view of Osiris maintenance procedure.

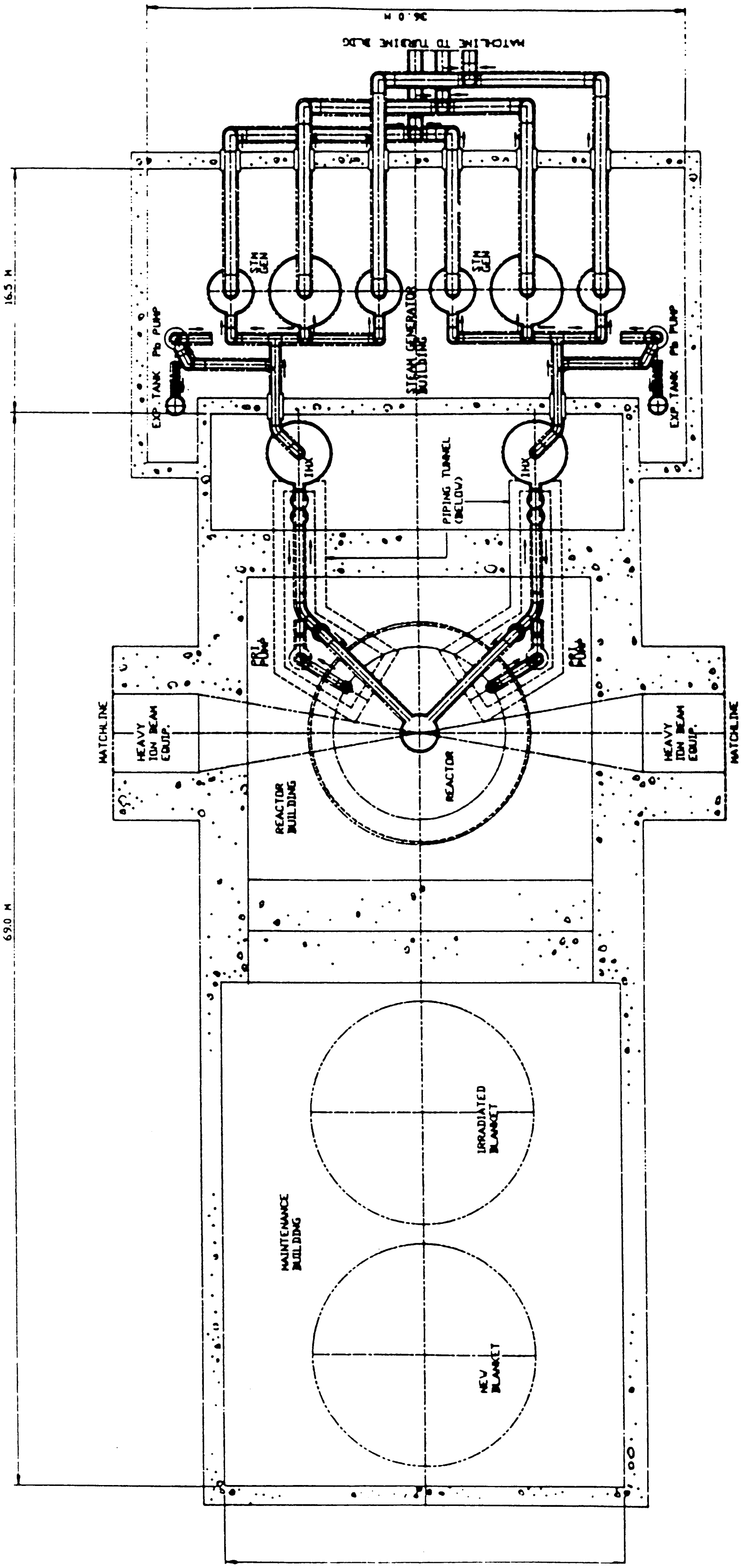

Fig. 6.2. Plan view of Osiris maintenance procedure.

design stage of a project is something of a novel practice. Retrofit operations are extremely expensive and not nearly as successful as accomplishing these tasks by design. A review of current practices in existing nuclear and hazardous materials handling facilities (for retrofit operations in using this type of equipment) and the projected remote maintenance and operation requirements of the current tokamak designs indicates that this practice of advanced work systems integration at the conceptual design stage may be well justified.

6.4 MAINTAINABILITY OF THE SOMBRERO PLANT

A methodology similar to the Osiris was used to develop an approach for remote maintenance of the SOMBRERO reactor. An analysis was performed on the sequence and type of activities required in order to remove and replace the reactor module assemblies and the optics within the reactor building. This analysis resulted in the definition of theaters and classes of operations for the SOMBRERO reactor. For the purposes of this study, the theaters of operation are defined as follows:

- Central Reactor Building Volume
- Outer Annular Reactor Building Volume
- Intermediate Heat Exchanger (IHX) Vault
- Optics within the Reactor Building
- Maintenance Hot Cell and Lay Down Area.

The theaters of operation were then cross-compiled with the identified activities required for equipment maintenance, removal, and/or replacement. An evaluation of the activities was performed to define the classes of operations that would be conducted. In an effort to determine a baseline case for overall remote handling equipment operational envelopes and equipment and component handling sequences (for maintenance activities), the activities that would define the classes of operation for the SOMBRERO reactor design are as follows:

- Upper Plenum / Inlet Pipe Removal
- Module Removal/Replacement
- Mirror and Optics Maintenance
- IHX Maintenance
- Reactor Support Equipment Maintenance
- Beam Handling Equipment Maintenance
- Hot Cell Operations.

Due to the large physical size of reactor building (dictated by the optics requirements), an innovative approach to crane operations and rigging and handling of components is necessary. For this case, both the polar crane and annular crane make use of the National Institute for Standards and Technology (NIST) high payload automated crane concept. This concept employs a modified Stewart platform where the hook and block-and-tackle are normally located. This platform allows for very stable control of heavy offset payloads at long distances from the cable drum and trolley assembly. The most unique design feature of SOMBRERO is the remote handling equipment designed to handle the chamber modules. Each of these modules is approximately 24-m tall and 8-m deep. Due to space restrictions in the center reactor building volume, each of these modules is designed to be removed and replaced one at a time. The removal sequence dictates that the module be lowered to the bottom of the inner cylindrical chamber, installed on a polar carriage assembly (which accommodates radial positioning), and tilted out of the lower access door via a transport carriage, through the annular space and into the hot cell facility (Figs. 6.3 and 6.4). This whole evolution is analogous to current practices in fuel bundle handling systems currently in use.

6.5 REMOTE HANDLING CAPABILITY AND UTILIZATION CONSIDERATIONS

There are several factors which affect remote handling equipment capabilities. These include, but are not limited to, the current trends in remote handling equipment development within the international community, the development efforts for an integrated graphics/CAD based control architecture (supervisory control system), the class of operations to be performed, the geometric limitations imposed by the intended theater of operation, the amount of technology transfer (from other industries and/or applications) to IFE's domain set, and the level of integration of the envisioned remote handling equipment with the baseline design of IFE.

The previously-stated maintenance operations may be considered to be rigorous for the level of remote handling equipment development that could be expected within the next ten years. It should be noted, however, that these operations are typically predicated upon the current level of implementation of remote systems within the nuclear community in this country as well as abroad. Several notable examples of remote-handling system developments that belie the predicted trends assumed above include those prototype systems currently being developed, tested, and demonstrated by various National Laboratories and industrial organizations to address the needs of the DOE/DoD Environmental Restoration and Waste Management Programs. These would include the hybrid multi-manipulator systems, fused sensor packages, and graphics-based control architectures being developed for underground storage tank remediation. Also, from the European offshore service community, several generations of a graphics-based supervisory

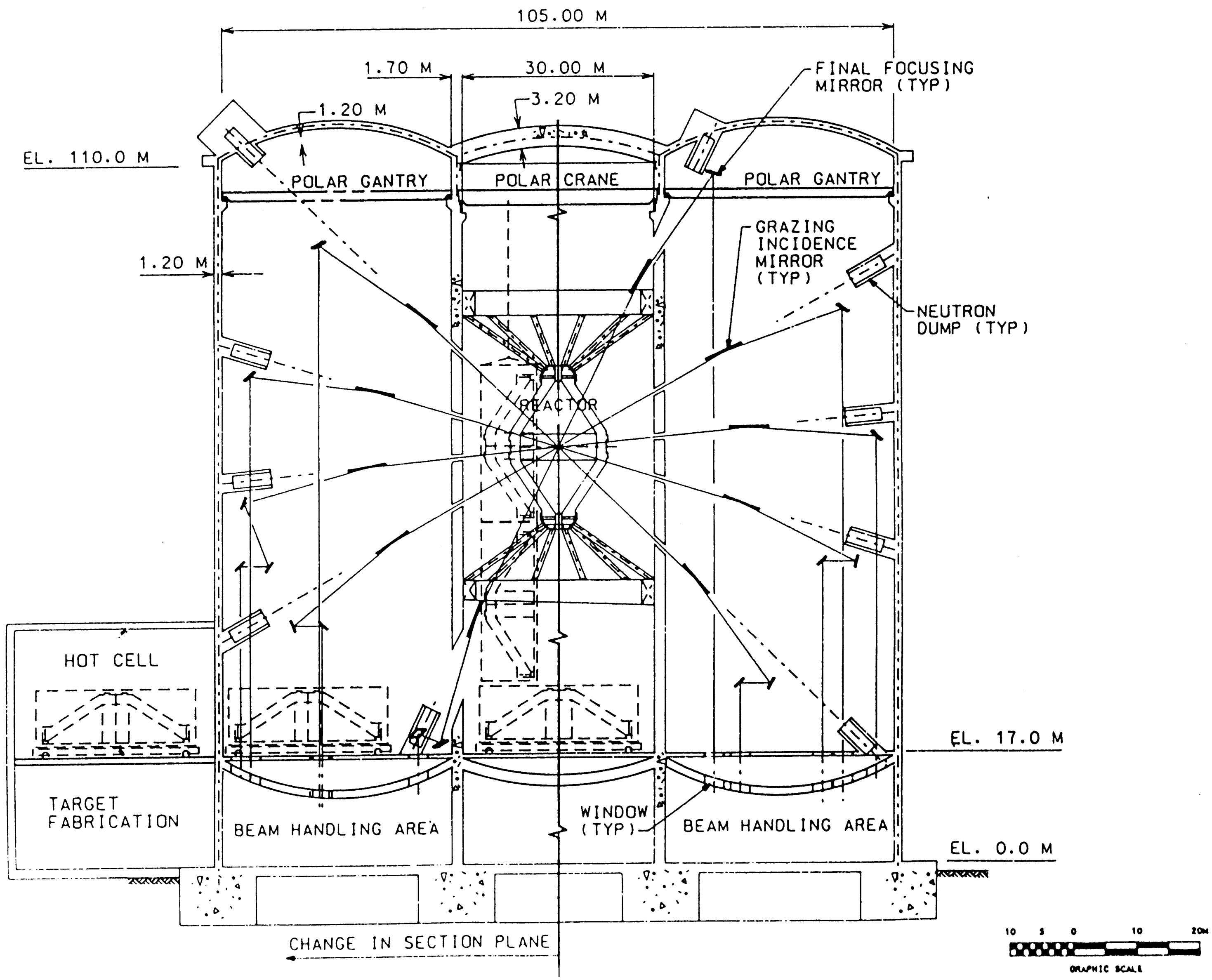

Fig. 6.3. Cross section view of SOMBRERO maintenance procedure.

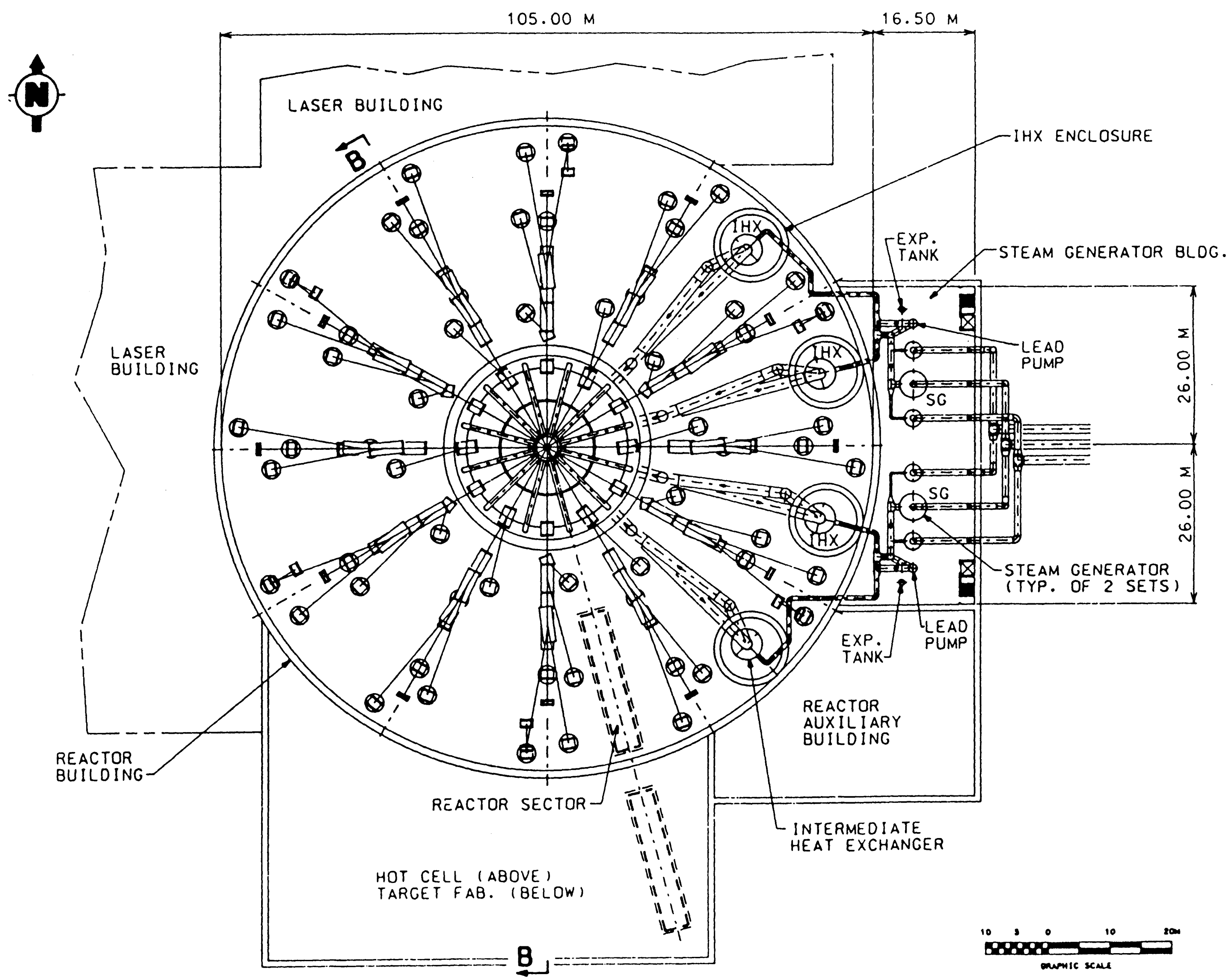

Fig. 6.4. Plan view of SOMBRERO maintenance procedure.

control system has been developed, tested, demonstrated, and implemented. These systems are controlling remotely operated vehicles (ROVs) with manipulator based NDT and work-package end effectors (e.g., cleaning and cutting tools) in a dynamic unstructured 3–D environment associated with sub-sea operations and maintenance activities at extreme depths. (They have been tested at depths of 1000 meters).

There are several assumptions underlying the remote maintenance approach discussed here:

- The plant is assembled with appropriate reference marks, types of bolts, fittings, and accessories so that robotic equipment may be used to its highest potential.
- Task performance is automated to the greatest possible extent, and the remote handling equipment is an integral component of the facility design, construction, and operation.
- A computer data base and documentation including a 3–D model are available in conjunction with physical reference points in IFE allowing automatic and precision indexing of robots.

Each of these assumptions is based upon the complexity of IFE and on the technology-based driver for a graphics-based control system. Given the current state of the art of positioning systems and their integrated use in closed loop control of remote system hardware, it is very likely that a combination of these positioning systems and a graphics-based control architecture would allow for the automated deployment and positioning of the remote handling equipment to the necessary degree of accuracy. Once again, these assumptions are based upon observations of currently available control systems and sensor packages that are being used in other industrial theaters of operation and the continued research and development efforts to further these applications. These types of systems and research trends can be observed in the manufacturing (flexible automation), construction (automated heavy construction equipment with integral force reflective feedback), environmental restoration (remote systems being developed for DOE/DoD cleanup operations), and the military (Bradley tank operating systems) sectors.

Other assumptions are based on considerations that would apply whether one were using automated or tele-presence type remote-handling equipment. These assumptions are as follows:

- The remote handling equipment electronics and support equipment (cameras, etc.) would be able to tolerate the intense radiation fields
- All of the required remote handling equipment is available when needed with no time scheduled for the design, fabrication, and testing of the requisite equipment

- All access locations are fully staffed and have a full complement of equipment and necessary support services required to allow parallel, simultaneous operations where required.

The configuration concepts of several state-of-the-art remote maintenance equipment are presented in Appendix E.

6.6 REFERENCES FOR CHAPTER 6

6.1 D. Orvis et al., "Guidebook for RAM Analysis," General Atomics Company Technical Report, ONWI-334 (April 1981).