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SHIELDING AND MAINTAINABILITY IN AN EXPERIMENTAL TOKAMAK

M. A. Abdou*
Argonne National Laboratory
Argonne, Illinois 60439

G. Fuller
McDonnell Douglas Astronautics Company
St. Louis, Missouri 63166

E. R. Hager
General Atomic Company
San Diego, California 92138

W. F. Vogelsang
University of Wisconsin
Madison, Wisconsin 53706

1. Introduction

It has long been recognized by the fusion community that provisions must be made for remote maintenance for all tokamak reactor components inside the toroidal field (TF) coils (e.g. first wall, blanket, bulk shield, etc.). This does not imply, however, that all maintenance-related operations have to be carried out by remote means. For example, there is much equipment located in the reactor building outside the TF coils that has to be maintained. Furthermore, there are many operations such as planning, viewing, connects/disconnects, and adjustment of maintenance equipment positions that can be made inside the reactor containment building exterior to the TF coils.

Therefore, a critical issue that has to be resolved in developing a complete maintenance plan for the next generation of experimental tokamak reactors such as ETF and INTOR is whether there is a net benefit from designing the reactor for human access into the reactor floor within a short time (a few hours to one day) after shutdown so that some maintenance operations can be carried out in contact and/or semi-remote mode. From maintenance plan standpoint, the benefit from personnel access is primarily a reduction in the total downtime and hence an improvement in the reactor availability. The principal penalty is an increment in the capital cost for the additional shield that is required above and beyond that necessary for radiation protection of the reactor components.

This paper presents the results of an attempt to develop an understanding of the various factors involved. This work was performed as a part of the task assigned to one of the expert groups on the International Tokamak Reactor (INTOR). However, the results of this investigation are believed to be generally applicable to the broad class of the next generation of experimental tokamak facilities such as ETF.

The shielding penalties for requiring personnel access are quantified in Sec. 2. This is followed by a quantitative estimate of the benefits associated with personnel access in Sec. 3. Section 4 compares the penalties to the benefits and develops conclusions and recommendations on resolving the issue.

2. Penalties of Personnel Access

In the absence of penetrations, a properly designed magnet (bulk) shield is capable of reducing the biological dose in the reactor hall to ∿1 mrem/hr within 24 hr after shutdown. This dose level permits a person to work continuously (40 hr/wk) without exceeding the ICRP guides for occupational exposure. The presence of major penetrations such as those for neutral beams, divertors, and vacuum pumping results, however, in substantial radiation streaming into the reactor building.[1] This will result in strong activation of the equipment located at the outer end of the penetration (e.g. beam injector components and walls), reactor building liner, reactor support frame, overhead cranes, poloidal coil, located outside the bores of the TF coils, and all equipment located in the reactor building. For the preliminary INTOR design concept in the presence of 0.8-m diameter beam ducts, detailed calculations resulted in the following estimates of the biological dose in the reactor building.

Time After Shutdown	Dose (mrem/hr) Outside the Injector Walls
0	6×10^6
12 hr	4×10^4
1 day	2×10^4
1 wk	1×10^4
1 mo	1×10^4
6 mo	3×10^3

Such a biological dose is too high to permit personnel access for any reasonable period of time.

For personnel access to be feasible, additional shielding must be provided to prevent radiation streaming into components located in the reactor building. Our objective here is to make an approximate estimate of the cost of this additional shield. To do this one must define an acceptable biological dose and a method of shielding.

The ICRP rules limit the maximum individual occupational exposure to 1.25 rem/quarter. This translates into a dose limit of 2.5 mrem/hr to a person working the entire quarter on 40 hr/wk basis. Another quasi-legal principle is to reduce the dose as low as reasonably achievable (ALRA). A measure of environmental impact that is presently receiving much attention is the total cumulative dose to the entire work force. Prudent practices require keeping the total cumulative dose (person-rems) as low as possible. Our evaluation suggests that for the purpose of gaining human access the design target should be to reduce the biological dose in the reactor building to ≤1 mrem/hr within 24 hr after shutdown.

One theoretical method of reducing the biological dose in the reactor building is to employ materials (for constructing all components outside the bulk shield) that do not transmute under neutron irradiation to radioisotopes with half-lives longer than a few minutes or hours. In practice, there is no suitable material to serve this purpose.

Radiation shielding is the only effective means of

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limiting the biological dose rate in the reactor building. There are two methods of shielding against radiation streaming from penetrations. The first is to employ a shield plug that completely closes each penetration at all times the neutron production is not zero. The principal difficulty here is that the functional requirements of some penetrations require that these penetrations be open during part of or all of the plasma startup and burn times. For example, neutral beam injection during the startup is accompanied with a substantial neutron yield from the heated plasma. Furthermore, if INTOR has to be driven, beam injection will also be necessary during the peak power portion of the plasma burn. It is not clear at present whether vacuum pumping (for the plasma chamber) during the plasma burn will be necessary. Holes for divertors, if a divertor is used, will of course have to remain open during the plasma burn.

The only shielding option whose viability is not subject to uncertainty is a local exterior shield that surrounds all penetrations and functional end equipment (i.e. equipment located at the outer end of the penetration such as a vacuum pump, beam injector, or a detector). This shield is always reauired for radiation protection of reactor components, but the magnitude of radiation attenuation it has to provide is larger if personnel access into the reactor building after shutdown is to be permitted. Multidimensional transport calculations and nuclear analysis effort carried out for INTOR shows that the largest and most costly requirement for personnel access is the additional shield around the functional end equipment. The largest portion of this shield is that required for the beam injectors because of their large size and the correspondingly large exterior surface area that has to be covered. A reactor system in which the opening of the neutral beam duct at the first wall is 0.8 m in diameter was analyzed. The beam duct was assumed to have a uniform cross section and connected to the beam injector at a location that is 3 m away from the first wall. The size of the beam injector was taken to be 10 m long, 6 m wide, and 6 m high. Based on previous studies for experimental power reactors, this system is roughly within the range of what can be expected for INTOR. For this system, it was found that ∿50-cm thick shield providing radiation attenuation and induced activation characteristics similar to that of a mixture of stainless steel and boron carbide plus lead need to surround the exterior surfaces of the beam injectors in order to reduce the biological dose rate in the reactor building below 1 mrem/hr within 24 hr after shutdown. This biological dose rate varies with time after shutdown as follows (for a neutron wall load of 1.6 MW/m^2):

Time After Shutdown	Dose (mrem/hr)
0	350
12 hr	14
1 day	0.8
1 wk	0.3
1 mo	0.25
6 mo	0.09

These calculations were made for an operating period of 3 mo, but it should be noticed that the level of radioactivity reaches ∿50% of the maximum after only a few days of operation.

An important conclusion obtained in the course of this assessment is that the use of the so-called "low-activation" materials such as aluminum are not useful for shielding components in the reactor building for several reasons: (1) the activity of ^{24}Na produced in aluminum (half-life ∿15 hr) requires several days of decay to reach an insignificant level; (2) aluminum is a poor neutron attenuator; therefore, for the same thickness of material a higher neutron leakage will obtain, leading to higher activation of building liner, structural torque frame, etc.; and (3) aluminum is a poor attenuator for gamma rays; therefore, more decay gammas from deeper regions of the shield will reach its surface and escape into the reactor building.

Penetrations with cross-section area smaller than those of the neutral beam will require less shield (smaller thickness) around their functional end equipment. The ducts for vacuum pumping (plasma chamber evacuation) will have roughly the same cross-section area as the ducts for neutral beams except that the ability to bend the vacuum pumping ducts significantly reduces radiation streaming.

Table I shows a summary of the cost of shield required around the functional end equipment of the various types of peentrations. Approximately 80% of this cost is attributed to the requirement of personnel access. These cost estimates are based on a unit cost of $70,000/$m^3$ of the shield (∿12$/kg for physical density of 5800 kg/m^3). This cost includes material, fabrication, and cooling expenses. Other relevant assumptions are indicated in the table.

The largest cost item is that of the shield around the beam injectors because of the large surface area around each injector. The shield for the vacuum pumps is included in Table I and it is assumed that no divertor is incorporated. The total cost of the additional shield strictly required for permitting personnel access is ∿89 M$. This is the cost penalty of personnel access.

It must be noticed that this shield cost penalty is very sensitive to certain technology choices as indicated in Table II. For example, if a divertor is incorporated the divertor shield increment attributed to personnel access is estimated to be ∿38 M$. The use of rf heating instead of neutral beam reduces the cost of shielding significantly for several reasons: (1) the feasibility of making bends in rf ducts; (2) larger power density per unit area at the first wall makes rf ducts smaller than those for neutral beams; and (3) the flexibility in geometrically locating the rf generator. Notice that the use of negative ion deuterium sources (all calculations above are based on D^+) will also result in a significant reduction in the cost of the shield. If rf heating is used and no divertor is employed the total cost penalty of shield for personnel access is only 48 M$ compared to 120 M$ for the neutral beam/divertor case.

3. Incentives for Personnel Access

In Sec. 2 the penalties of the additional shielding to permit personnel access were examined. In this section the benefits that can be obtained from enabling maintenance personnel to enter the reactor building within 24 hr after shutdown are assessed. The two general maintenance scenarios considered here are: all-remote and contact/partial-remote. The maintenance scenario has been developed in enough detail to provide estimated failure frequency and maintenance plan data for major reactor components.

The areas of the reactor building that have been considered for contact or partial-remote (this can also be described as contact assisted remote) maintenance include all accessible components or systems that are external to the reactor main (bulk) shield. This generally includes instrumentation and control diagnostics, cooling systems, power leads, and the tritium recovery system as well as a portion of the maintenance operations on many components inside the shield. Both the all-remote and the contact/partial-remote maintenance

TABLE I. Cost of Shield for Personnel Access

Component with Penetration	Cost of Shield Around End Equipment (Based on 70 K$/m^3)	Cost of Portion of Shield for Personnel Access	Remarks
Neutral beams	80 M$	65 M$	7 injectors (each is 10 × 6 × 6 m^3)
Diagnostic	12 M$	a	50 detectors (each is 1 × 1 × 1 m^3)
Vacuum pumps	21 M$	16 M$	30 vacuum ducts (2 pumps per duct)
Others	10 M$	8 M$	
TOTAL	123 M$	89 M$	

[a] The shield around the instrumentation and control "end equipment" appears to be always required for radiation protection of this equipment from background radiation.

TABLE II. Effect of Technology Choices on Cost of Shield for Personnel Access

Option	Total Cost of Shield for Personnel Access
Neutral beams, divertor[a]	120 M$
Neutral beams, no divertor	89 M$
rf (or D$^-$), no divertor	48 M$

[a] The cost of the shield for the divertor can be much larger than what is assumed here, depending on the particular divertor concept considered.

TABLE III. Comparison of Time Required to Perform Typical Tasks

	LASL[a]	MIT[b]	NASA[c]	MBA[d]	CEA[e]
Two-armed man					
Unsuited	1	1	1	1	1
Suited	-	-	-	8	-
Mechanical M/S					
Two-arm	8	8-10	8	8	2-8[f]
One-arm	16	-	16	-	-
One-arm EMM					
Position control[g]	80	40-50	64	55	10-30
Switch control[g]	480	80-100	640	-	50-100
Crane - Impact wrench[g]	>500	>100	>600	>500	>100

[a] Based on installing bolt and lifting sling.

[b] Based on eight definitive tasks.

[c] Based on analysis and literature survey.

[d] Based on typical valve changeout.

[e] Based on variety of extensive tasks using different manipulators.

[f] Multiply by 1.4 for untrained operators.

[g] No force feedback.

external to the reactor main (bulk) shield. This generally includes instrumentation and control diagnostics, cooling systems, power leads, and the tritium recovery system as well as a portion of the miantenance operations on many components inside the shield. Both the all-remote and the contact/partial-remote maintenance schemes are strongly design-sensitive and will require continuing attention during the machine conceptual design phase for proper implementation.

3.1 Contact and Partial-Remote Maintenance

The three major maintenance operation methods are contact, all-remote, and partial-remote. A wide range of partial-remote operations can exist between the contact and all-remote extremes and this is the area in which many of the INTOR maintenance operations may fall if adequate shielding is provided.

Contact maintenance is defined as the use of direct hands-on or conventional techniques including hand-held and guided tools to repair or maintain components or systems. Maintenance operations may include: inspection, damage assessement, and repair for forced outages as well as scheduled operations in connection with preventive maintenance.

All-remote maintenance operations are those which must be accomplished without the benefit of any human assistance within the immediate area of operation. The actual tasks are performed by manipulators (some with force feedback) or by special tools and fixtures which may be guided or assisted by manipulators or cranes. These operations generally require 8 to 500 times longer to perform the same task than with contact work. Table III, taken from a recent remote systems seminar,[2] compares the time to perform various remote tasks with contact work.

In the case where some personnel access is available (e.g., during the period when all shielding is in place, but preparations are in progress for unshielded remote work) partial-remote maintenance may be carried in order to minimize the time lost with all-remote operations. Varying amounts of contact maintenance operations can be performed on different components depending on the design of the equipment and the task involved. Those operations sometimes called "semi-remote" (including long-handled tools and temporary or shadow shields) are included in the partial-remote category for purposes of this analysis.

3.2 Utilization of Partial-Remote Maintenance on INTOR

Operations at fission reactors provide many examples of partial-remote maintenance. The use of long-handled tools in water-shielded pools allows significant savings in time and optical equipment. Temporary or shadow shields and special tools are frequently utilized for maintenance tasks such as changing filters.

An example of a partial-remote maintenance task on a fusion reactor with adequate biological shielding to provide personnel access soon (say 24 hr) after shutdown is as follows: An ion source on a neutral beam injector has failed. The neutral beam assembly is shielded but the ion source is separately shielded and detachable along with its shield. Electrical and cooling services are supplied through the shield and have conventional external disconnects. As soon as allowable after shutdown, maintenance personnel enter the reactor building and disconnect the electrical and cooling supplies as well as the ion source shield structural fasteners. Tooling and fixtures are set up locally for the actual source removal operation. The personnel temporarily move to a safe distance or behind a shadow shield while the remote or semi-remote equipment removes the source and shield assembly and reinserts a new source and shield assembly. A temporary shielding cover is placed over any exposed radioactive portions of the removed ion source and shield assembly. After shielding is in place, maintenance personnel can reapproach the neutral beam and complete the ion source hookup. Alternatively, the entire change-out could be accomplished by personnel utilizing shadow shielding and long-handled tools and/or cranes. About 25% of the original remote work remains.

Significant savings in time, complexity of reactor components, disconnects, and remote equipment can be realized when compared to an all-remote operation. Many other opportunities exist for more efficient operations by use of partial remote operations on shielded reactor components such as cryopumps, control and instrumentation diagnostics, divertors, etc.

3.3 Utilization of Contact Maintenance on INTOR

Obviously, the greatest maintenance time savings occur when an all-remote operation can be replaced by a contact maintenance operation. If areas exterior to the reactor shield can be made available by personnel access about 24 hr after reactor shutdown, a number of very difficult remote operations are eliminated.

Control and instrumentation diagnostic components external to the shield represent a class of maintenance tasks which can be rather trivial under a contact maintenance scenario but which will create challenging design and operational problems if remote manipulations are required. Replacement or repair of degraded optics and vacuum isolation valves are typical tasks. Diagnostic modification and realignment are tasks which generally require excellent viewing capabilities and an extremely delicate touch. Examples are laser optics and photo-diode replacements. Considerable equipment and time savings are possible if these maintenance jobs are contact. Many reactor control or instrumentation components require shielding for self-protection greatly complicating the inspection, repair, and replacement tasks with all-remote operations.

Breakdown of remote maintenance equipment can also create serious operational problems and add to reactor downtime. These breakdowns will usually occur during remote operations and therefore require special recovery equipment and design provisions. Each remote operation must be examined to identify equipment failure modes. Generally, a shielded area must be provided to which failed remote equipment can be moved for hands-on maintenance. Failing this, additional remote equipment must be provided. Reducing the number of remote operations required obviously will reduce these tasks.

3.4 Inspection, Damage Assessement, and Repair

An important issue, which is difficult to quantify, relates to the amount of time required to identify reactor equipment problems. Closely related is the inspection of components to head off failure. When these tasks must be accomplished remotely, they will be forced to rely on remote viewing devices and considerably augmented instrumentation.

One source[3] states that localization and isolation functions related to corrective maintenance of electronic equipment genrally account for 60% of the total expended maintenance time. The proportion of downtime required to troubleshoot mechanical equipment is also a relatively large percentage of the total repair time.

Accomplishing the above tasks remotely will add significantly to the time involved. Television viewing is required in most cases since reactor equipment will be located in obscured positions and at relatively large distances from any shielding viewing windows that could be provided in the reactor building. TV systems should certainly provide depth perception in order to compensate the lack of all other human senses in a remote environment. With only remote viewing and instrumentation as an aide to fault identification and troubleshooting, considerable additional maintenance time should be expected.

Remote repair operations can actually create additional maintenance work due to unexpected incidents such as twist-off of bolts, cross-threading of fasteners, and the dropping of delicate parts. Many remote handling design techniques exist to help offset these problems, but the design solutions are often costly.

3.5 Impact of Use of Contact/Partial-Remote Maintenance

In order to quantify some of the expected benefits of utilizing contact/partial-remote maintenance where possible on the proposed INTOR reactor, an analysis of the data for an all-remote maintenance scenario developed earlier for INTOR was undertaken. Components, downtimes, manpower estimates, and personnel exposure times were examined in as much depth as possible at this early stage of the concept.

Maintenance plan data are categorized into scheduled and unscheduled maintenance periods depending on expected failure frequency, importance of the equipment to continued reactor operation, and redundancy provided. A preventive maintenance scenario of scheduled quarterly 28-day downtimes and scheduled 2-day weekly downtime (for 32 wk) is then pursued.

The critical path quarterly maintenance items are shown in Table IV. All-remote downtimes are compared with contact/partial-remote downtimes expected. Contact/partial-remote times are calculated from all-remote time estimates using divisors derived from remote handling experience, including data shown in Table III. The divisors chosen include considerable conservatism to ensure that time savings are not overestimated. The basic factor chosen is that a 5 to 1 reduction exists between an all-remote job and an all-contact one.

The blanket recoating operation all-remote downtime, estimated as 18 days, is divided by 1.43 to reflect the fact that only a portion of this operation can be done in the contact mode. This implies that ~38% of the remote work can be replaced by contact work. The downtime for the new contact/partial-remote operation is therefore 12.6 days and the time saved is obviously 5.4 days. Of the 12.6 days now required for this task, 1.35 days (11%) are accomplished by contact work. Thus, a major portion of the downtime on this job is still accomplished in the remote mode. These proportions were chosen from a preliminary analysis of the operations for this maintenance task.

A similar approach is used for the second critical path item shown, replacing limiter plates. A portion of these first two tasks shown in Table IV is assumed to be accomplished in parallel and the entire experiment exchange task is assumed to be completed while the

TABLE IV. INTOR Quarterly Preventative Maintenace Downtime (Critical Path)

	All Remote		Partial-Remote
	Total Downtime (days)	Net Downtime (days)	Net Downtime (days)
Blanket - withdrawn four sectors and recoat walls	18	18	12.6
Limiters - replace 8 plates from 2 sectors	8	6	3.6
Experiment exchange - replace 3 first-wall/ blanket modules	8	0	0
Maintenance equipment downtime (average)		0.4	0.1
Shutdown and startup		1.0	1.6
TOTALS		25.4	17.9
Quarterly downtime assumed		28.0	18.0

other tasks were in progress. A total of 19 other quarterly or annually scheduled maintenance items are identified, but all are of shorter duration than critical path items and can be performed in parallel. Thus, the net downtimes shown are used to calculate contact/partial-remote times for these pacing items. Finally, additional downtime is allowed for maintenance equipment failures and shutdown and startup of the reactor. A total quarterly downtime of 28 days for the all-remote mode and 18 days for the contact/partial-remote method is assumed from these estimates.

The weekly maintenance plan includes two items: neutral beam ion sources and divertor bombardment plates. Both systems can be serviced in parallel during the one-day downtime available under the all-remote maintenance plan. With the contact/partial-remote mode, these weekly items are completed in 9.6 hr using a divisor of 2.5. As discussed in the example previously given, ~25% of the original remote work remains. The total weekly downtime is 48 hr for either maintenance mode.

Since no downtime reduction is predicted for weekly scheduled maintenance under the contact/partial-remote scheme, the savings per quarter is 10 days for a total of 40 days per year.

In a similar manner, the estimates of manpower for the all-remote maintenance plan were used to calculate manpower saved when using the contact/partial-remote maintenance scheme. Since contact work in the reactor building will add to personnel radiation dose, the number of contact man-days is also calculated.

The savings in the unscheduled downtime per operating year is estimated as 80 days. Manpower is saved at the rate of 416 man-days per operating year (24-hr days). Contact work accomplished will require 104 man-days per operating year.

4. Summary, Conclusions, and Recommendations

Two maintenance plans were analyzed for INTOR. The first employs all-remote maintenance operations and requires no access to the reactor building at any time during the useful life of the facility. The other is based on a partially-remote plan that combines remote, semi-remote, and contact operations in specific maintenance tasks. The semi-remote and contact operations are limited to components that are located outside the magnet bulk shield. Examples are instrumentation and control equipment, coolant lines, and power leads. Maintenance tasks on components inside the bulk shield envelope were assumed to be carried out remotely with the benefit of semi-remote or contact operations for some of the preparatory work (e.g. coolant lines and power leads disconnects/reconnect) when all shield is in place. A reasonably conservative, but preliminary, analysis shows that for most of the critical path maintenance tasks ~63% of the operations in the all-remote scenario remain as fully remote while the other 37% can be performed by contact or semi-remote means.

A major requirement of the partially-remote plan is for maintenance personnel to gain access into the reactor building a short time after shutdown to work in the reactor hall regions located outside the toroidal-field magnets. Multidimensional radiation transport calculations and nuclear analysis shows that additional shield is required around all functional equipment located at the outer end of all penetrations such as those for beam injection, vacuum pumping, divertors, and diagnostics. The amount, characteristics, and cost of this additional shield to reduce the biological dose rate in the reactor building to <1 mrem/hr at 24 hr after shutdown were determined.

It was assumed that the radiation level is the only factor that determines the feasibility of human access into the reactor building. Therefore, it was implicitly assumed that: (1) the environment of the reactor building is not contaminated with tritium, or more specifically maintenance personnel are not required to use breathing apparatus that could severely reduce their productivity; and (2) the environment of the reactor building during maintenance periods is normal air which implies that either the reactor building is not evacuated under normal operation or, alternatively, it can be repressurized within the 24-hr period allowed for radiaotive decay.

Table V presents a summary of the significant differences between no special shield/no personnel access plan and the partially-remote/additional shield/ personnel access plan. The conclusions from this comparative assessment are:

(1) The partially-remote plan significantly reduces the maintenance downtime (scheduled plus unscheduled) by ~120 days per operating year relative to the all-remote plan. Therefore, the estimated reactor availability of 0.285 for the all-maintenance plan increases to 0.38 for the partially-remote plan. This 33% improvement in availability is the most significant potential benefit of the partially-remote/additional shield/personnel access scenario.

(2) The economic penalty of the partially-remote plan is the capital cost of the additional shield around the beam injectors, vacuum pumps, and other functional equipment located at the outer end of penetrations. Assuming neutral beams are used for plasma supplementary heating and no divertor is incorporated the cost of material, fabrication, and cooling of this additional shield is estimated to be ~89 M$ when the most efficient shielding materials are used. The merits and disadvantages of employing cheaper but less efficient shielding materials such as borated water and concrete have not been evaluated but could possibly reduce the shield cost penalty. If the capital cost of INTOR is in the range of 800 M$ to 1 B$, then the 89 M$ for the additional shield represents an in-

TABLE V. Summary of Significant Differences Between All-Remote and Partially-Remote (with Personnel Access) Maintainance Plans

	All Remote	Partial Remote (with Personnel Access)
Savings in downtime, days per operating year	0.0	120
Reactor availability, %	28.5	38
Manpower requirements:		
Total person-hr per calendar year	57,288	49,443
Radiation person-hr per calendar year	0.0	1,963
Cost items, M$:		
Capital cost of remote maintenance equipment	50	45
Maintenance labor cost per calendar year	19	16.5
Cost of additional shield for personnel, access with neutral beams and no divertor	0.0	89
Increase in radiation exposure due to personnel access (person-rem per calendar year)	0.0	2.0

crement in the capital investment of the facility in the range of ∿9% to 11%.

(3) With the lack of an established cost-benefit analysis methodology, there are sufficiently convincing arguments that suggest the use of the ratio of the capital cost to availability as a comparative figure for experimental facilities such as INTOR. The cost per unit benefit for INTOR with the partially-remote/ additional shield/personnel access scenario is ∿17% lower than that with the all-remote/no-special shield/ no-access maintenance plan.

(4) Another way to quantify the benefits of the partially-remote plan is to examine the impact on the allowable failure frequency and the required redundancy for the individual reactor components. Since for a given failure the partially-remote scenario requires less downtime for repair or replacement than the all-remote plan the failure frequency can be allowed to be higher for the former for a fixed target availability. Alternatively, the required level of redundancy with the all-remote can be substantially reduced with the partially-remote plan. Examining the allowable failure frequencies for individual reactor components in the all-remote plan shows that they can be increased by ∿40% for the partially-remote plan.

(5) The cost of the additional shield for personnel access is sensitive to particular technology choices. If a divertor is incorporated on INTOR the cost of the additional shield increases from 89 M$ to ∿120 M$. Replacing neutral beams with rf heating reduces the cost of this shield from 89 M$ to ∿48 M$.

(6) Since it is impossible to reduce the biological dose in the reactor building to zero, maintenance, personnel working in the reactor building will receive a radiation dose. The additional shield considered for the partially-remote plan is sufficient to reduce the total cumulative dose to all maintenance personnel to ∿2 person-rem/calendar year. This is more than two orders of magnitude lower than the radiation exposure to maintenance personnel in current fission facilities.

(7) The partially-remote maintenance plan has favorable impact on reactor facility design requirements, capital cost of maintenance equipment, and labor cost.

(8) Research and development requirements for maintenance equipment are extensive for both the all-remote and partially-remote maintenance scenarios. However, the risks in the maintenance equipment development appear to be somewhat less for the partially-remote plan.

Important recommendations derived from the above conclusions are:

(1) The most attractive maintenance scenario appears to be the one that combines contact, semi-remote, and remote operations so as to achieve an optimum benefit-to-cost ratio for the experimental facility. Finding this optimum should be a key area that must be addressed, in all its aspects, in the INTOR development effort.

(2) The space in the reactor hall inside the reactor containment building but outside the main bulk magnet shield should be designed for personnel access within one day after shutdown. Material choices and design options that achieve this goal at a minimum cost should be comprehensively investigated. The feasibility of shield plugs for the major penetrations should be closely examined.

(3) Alternatives to technology choices requiring very large penetrations such as neutral beams and divertors should be seriously examined.

(4) The tradeoffs between the location of the vacuum boundary and maintenance plan should be investigated.

REFERENCES

1. M. A. ABDOU, "Problems of Fusion Reactor Shielding," Georgia Institute of Technology, GTFR-10 (1979).

2. F. C. DAVIS, "Fuel Processing Plant Design," *Proc. Seminar on Remote Systems for Fusion Reactors*, Oak Ridge National Laboratory, April 27, 1979.

3. B. S. BLANCHARD, JR., and E. E. LOWERY, *Maintainability and Practices* (McGraw-Hill, 1969), p. 113.