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REMOTE SYSTEMS REQUIREMENTS OF THE HIGH YIELD LITHIUM INJECTION FUSION ENERGY (HYLIFE) CONVERTER CONCEPT

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REMOTE SYSTEMS REQUIREMENTS OF THE HIGH YIELD LITHIUM INJECTION FUSION ENERGY (HYLIFE) CONVERTER CONCEPT*

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ABSTRACT

Remote systems will be required in the High Yield Lithium Injection Fusion Energy Converter power plant proposed by Lawrence Livermore Laboratory. During inspection operations, viewing of the chamber interior and certain pumps, valve fittings and welds must be done remotely. Ideas for remote maintenance of laser beam blast baffles, optics, and target material traps are described. Radioisotope sources and their distributions, and exposure rates at various points in the reactor vicinity are presented.

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INTRODUCTION

During the past year, Lawrence Livermore Laboratory, in conjunction with nuclear industry, analyzed a concept for an inertial confinement fusion electric power plant. The High Yield Lithium Injection Fusion Energy (HYLIFE) converter incorporates many features of importance to designers of remote maintenance and inspection systems. This paper presents these features of the HYLIFE converter, outlines the perceived requirements for remote systems, and solicits creative ideas for meeting these needs from the remote technology community.

The evolving design of the HYLIFE converter has not yet included specific remote systems. However, a definition of the radioisotopes produced in the structural steel and activated target materials has recently been completed. This analysis indicates a need for remote systems at several points and times during inspection and maintenance in the HYLIFE power plant. General characteristics of the remote systems required by inertial confinement fusion power plants have been presented by T. G. Frank and L. A. Booth at the 25th Conference on Remote Systems Technology.[1] Many of their conclusions apply as well to the HYLIFE concept. In addition, the following paper provides specific information on the source term expected at different times in the operational life of the HYLIFE plant and emphasizes the unique features of the design.

GENERAL DESCRIPTION OF THE HYLIFE CONCEPT

The HYLIFE chamber is shown in Figure 1. This design has previously been described[2] and the environmental and safety features have been addressed.[3] As in previous LLL designs, the first-wall structural steel, chamber head and bottom are protected from the direct products of the fusion pellet by a region of flowing lithium metal. In HYLIFE, this lithium is injected as an array of jets through the injection manifold at the top of the chamber. The lithium leaves the chamber through a single large exit at the bottom and is then recirculated to the top of the chamber by a battery of 16 pumps, which are arranged around the central HYLIFE chamber as shown in Figure 2. Each set of 4 pumps supplies a portion of its total output flow to an intermediate heat exchanger, where the thermal energy is transferred to a secondary liquid sodium loop.[4] Radioactivity from activated structure, pellet materials and tritium is confined to the primary coolant loop area and the laser beam tunnels. This area is comparted by one and two meter thick concrete walls which provide shielding and seismic stability. The entire cell structure operates under an inert gas atmosphere to provide liquid metal fire safety. The gas will be circulated and tritium removed as part of tritium containment design. Throughout the primary coolant area, adequate clearance has been provided for access to valves, piping nozzles, and pumps for inspection and maintenance.

Inspection and maintenance of the chamber interior can be done through the top of the vessel by removing the central graphite plug or through the laser beam and target injection tubes on the sides. Periodic replacement of the blast baffles in the beam tubes will also be required.

HYLIFE CONVERTER CONCEPT

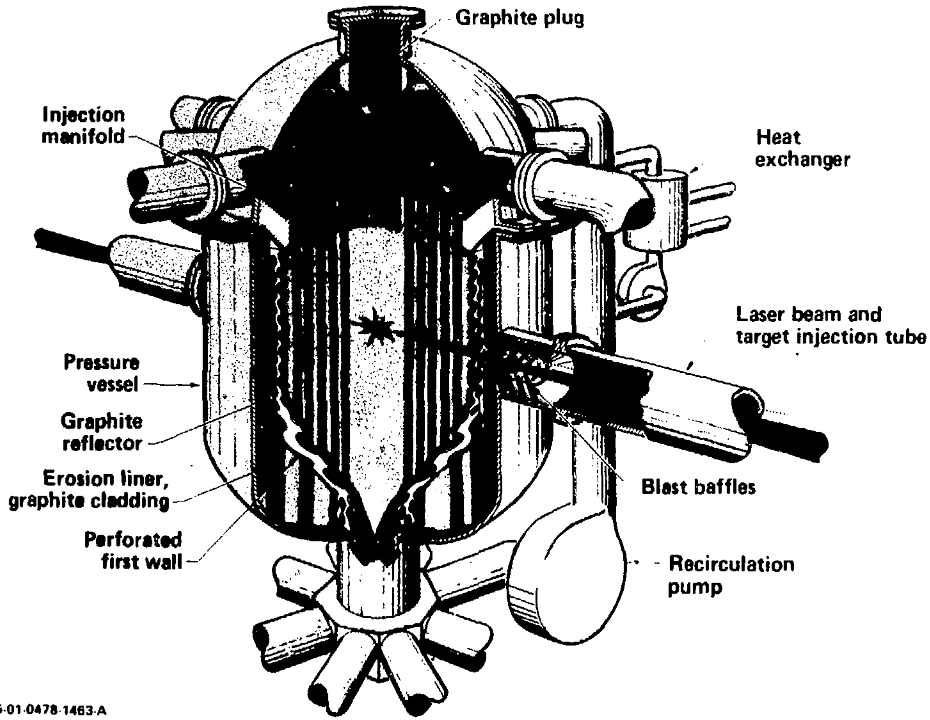
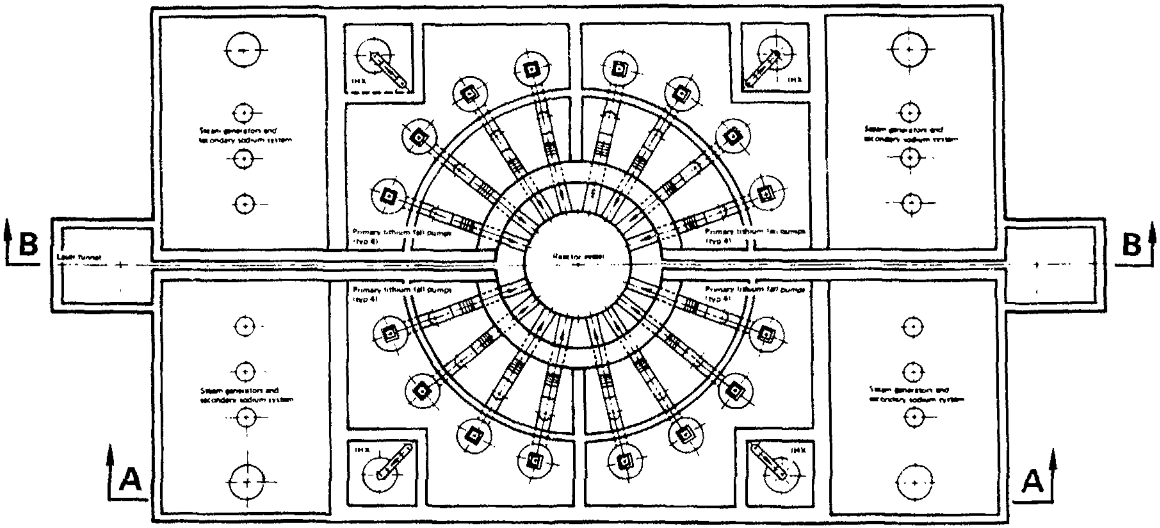


Figure 1


B
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Steam generators and secondary sodium system
Steam generators and secondary sodium system
Steam generators and secondary sodium system
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IHX
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Primary lithium fall pumps (typ 4)
Primary lithium fall pumps (typ 4)
Primary lithium fall pumps (typ 4)
Primary lithium fall pumps (typ 4)
A
A

Figure 2

Several features of the HYLIFE system are of particular interest to designers of remote systems. First, the one-meter effective thickness of lithium protection within the HYLIFE chamber reduces the rates of fast-neutron atom displacement damage and helium production in the structure to levels at which even the interior steel can be expected to survive for the entire 30-year plant life.[5] Therefore, large-scale remote replacement of the blanket material is not required in this design. No large-scale remote welding is required on the HYLIFE chamber or associated components. Movement of attachments to the vessel and subassemblies within the vessel is easily accomplished with standard overhead cranes after securing bolts are removed. The layout of the HYLIFE plant is much like that of a LMFBR, and those remote systems which will be needed for inspection and maintenance on the balance of plant components can probably be readily adapted from existing designs for breeder reactors.

A second consideration in the HYLIFE design is that activated corrosion products, tritium at a concentration of a few ppm, and radioactive target debris will be present in the lithium flow. These materials will be concentrated at various points in the primary coolant and fall circulation flow loops either through deliberate extraction processes such as tritium recovery or by spontaneous phenomena such as precipitation of heavy metal debris or intermettalic compounds at bends and valves in piping. Remote servicing or cleanup of these high-activity points will be required. It is worth noting, however, that specific activity at all points in the HYLIFE lithium flow is many orders of magnitude less than specific activity in the sodium of a LMFBR. Remote technology designed for the LMFBR primary loop environment should serve well for application in the HYLIFE lithium loop.

Finally, the HYLIFE conceptual design uses 2 1/4% Cr - 1% Mo ferritic steel as the primary structural material. This common low-alloy steel, when partially shielded by liquid lithium from the fast neutron output of fusion pellets, activates far less than costly and exotic alloys specially chosen for low induced radioactivity in magnetically confined fusion reactors (Figure 3). Since maintenance and inspection operations will be conducted with the reactor shut down, the induced activation in structural steel will be the major source of radioactivity determining the need for and design of remote systems for use in the vicinity of the HYLIFE chamber.

STRUCTURAL STEEL RADIOACTIVITY

The alloy composition of 2 1/4 Cr - 1 Mo steel is relatively simple. Therefore, few radioisotopes contribute to the total gamma activity in activated steel. Table I presents those isotopes and the time period during which each contributes a significant amount to the total gamma energy output from the activated structure. The isotopes are listed in order of the magnitude of their contribution to the gamma rate (MeV/h) from the interior steel zones at shutdown.

The radioisotopes induced in HYLIFE steel are quite unevenly distributed in the structure, as shown in Figure 4. Since the greatest amount of activity occurs in the interior zones of the chamber, self-shielding by the source material and by outlying zones of carbon and steel will be

RADIOACTIVITY OF CTR BLANKETS AFTER SHUTDOWN

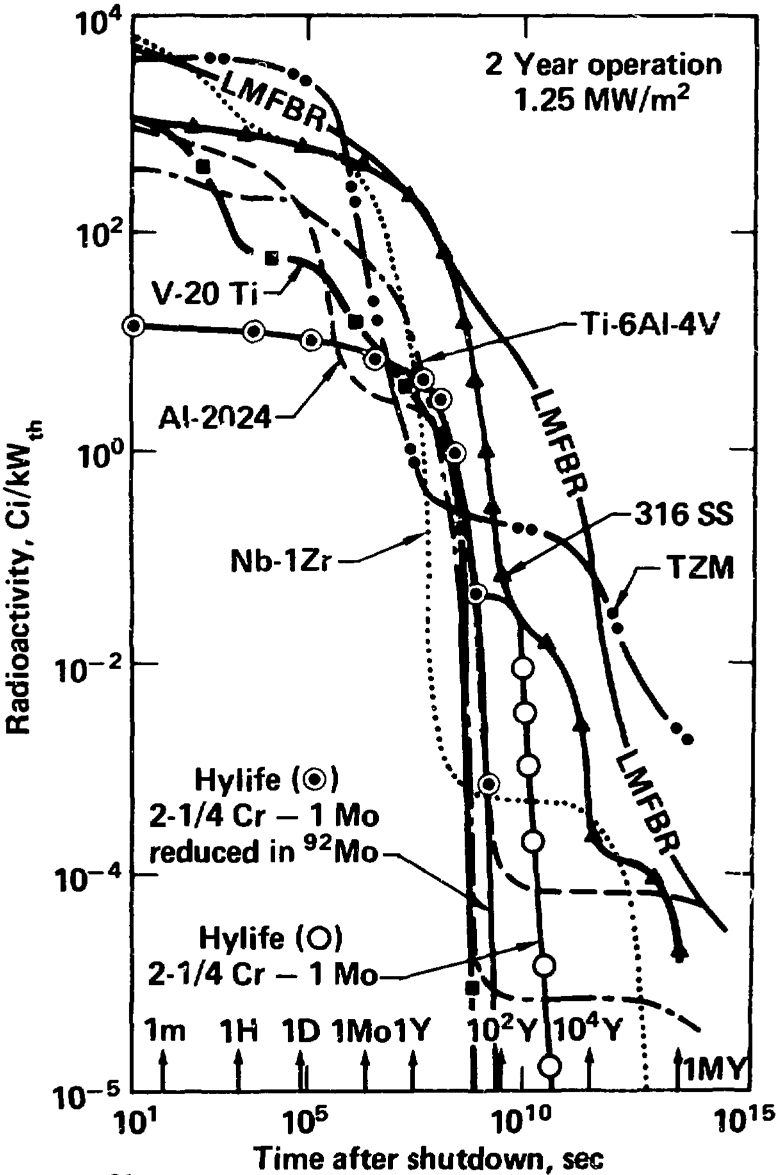

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Figure 3

Isotope	Parent	Half-Life	Gamma Energy (MeV)	Period of Significance
Mn-56	Fe-56	2.582 h	0.847 (100%) 1.81 (30%) 2.11 (15%)	Shutdown to 6 hours
Mn-54	Fe-54	313 d	0.835 (100%)	6 hours to 10 years
Fe-59	Fe-58	44.59 d	1.099 (56%) 1.292 (44%)	6 hours to 1 month
Mo-99	Mo-98	2.779 d	0.739 (15%) 0.181 (7%)	6 hours to 1 week
Mo-93	Mo-92	100 y	0.030 (85%)	Beyond 10 years

Table I: Significant Radioisotopes Present in HYLIFE Structural Steel.

LESS THAN SIX PERCENT OF INDUCED ACTIVITY RESIDES IN THE REACTOR EXTERIOR

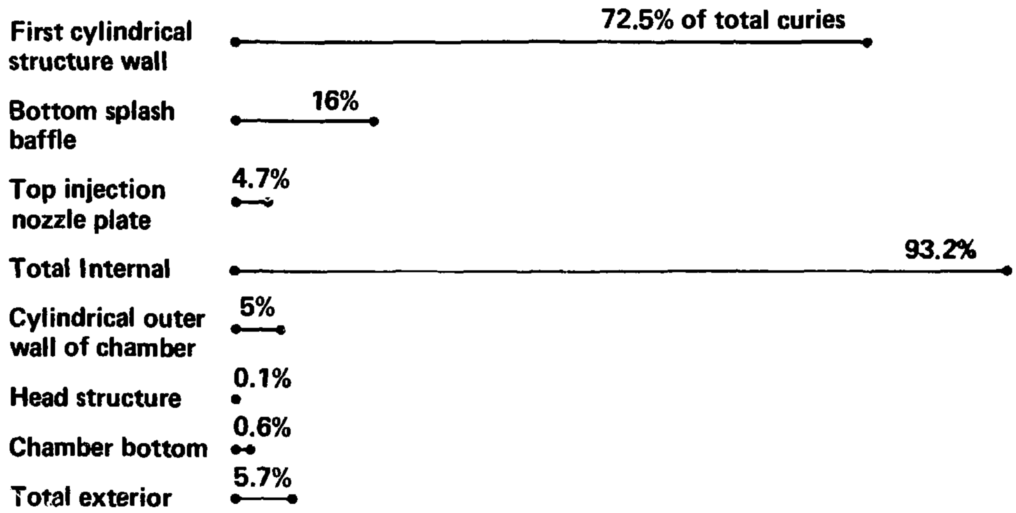

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Figure 4

significant factors affecting exposure rates outside the chamber. This shielding has been included in the exposure rate calculations which follow. The total curies of activity and total gamma-ray energy output rate in MeV/h are plotted in Figures 5 and 6 as functions of time following shutdown after a full-service plant lifetime. Although Fe-55 is an important contributor to total curies of activity in the long term, it is not a gamma emitter and does not directly bear on remote systems design considerations.

Remote instruments may be inserted into the chamber for periodic inspection or maintenance operations. These devices will be exposed to beta emissions from tritium, Fe-59, Mo-99, and possibly Mn-56. However, the gamma flux in the chamber is of more concern in properly shielding solid-state electronic components which may be part of remote television viewing systems and some manipulator mechanisms. In Figure 7, the gamma exposure rate at the center of the HYLIFE chamber is plotted as a function of time following shutdown after one year of full-power operation. Curves are shown for both a cylindrical surface source and a more realistic uniformly-distributed annular volumetric source with self-shielding considered. The shutdown levels will be greater for operating times in excess of one year. However, since Mn-56, Fe-59, and Mo-99 are already at saturation after a year of operation, the buildup of additional activity will follow Mn-54 production and will not exceed twice the shutdown activity at one year regardless of total operating time.

CURIES OF RADIOACTIVITY IN HYLIFE STRUCTURAL STEEL

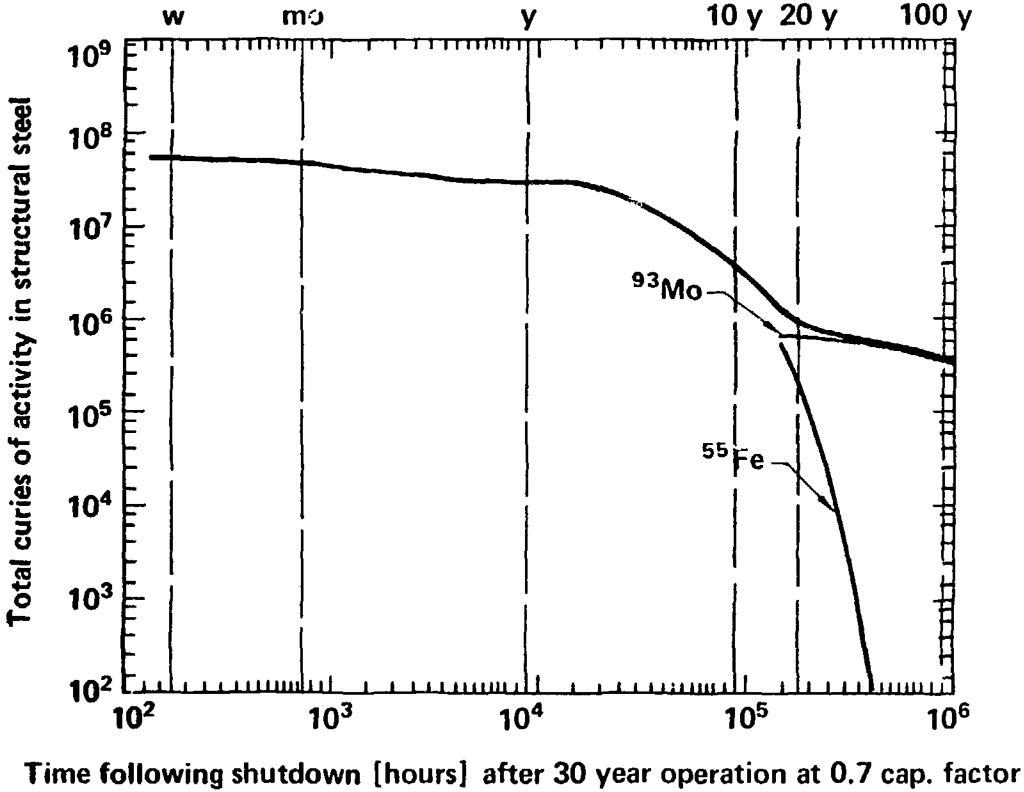

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Figure 5

GAMMA MeV/hour RATES FROM HYLIFE STRUCTURAL STEEL

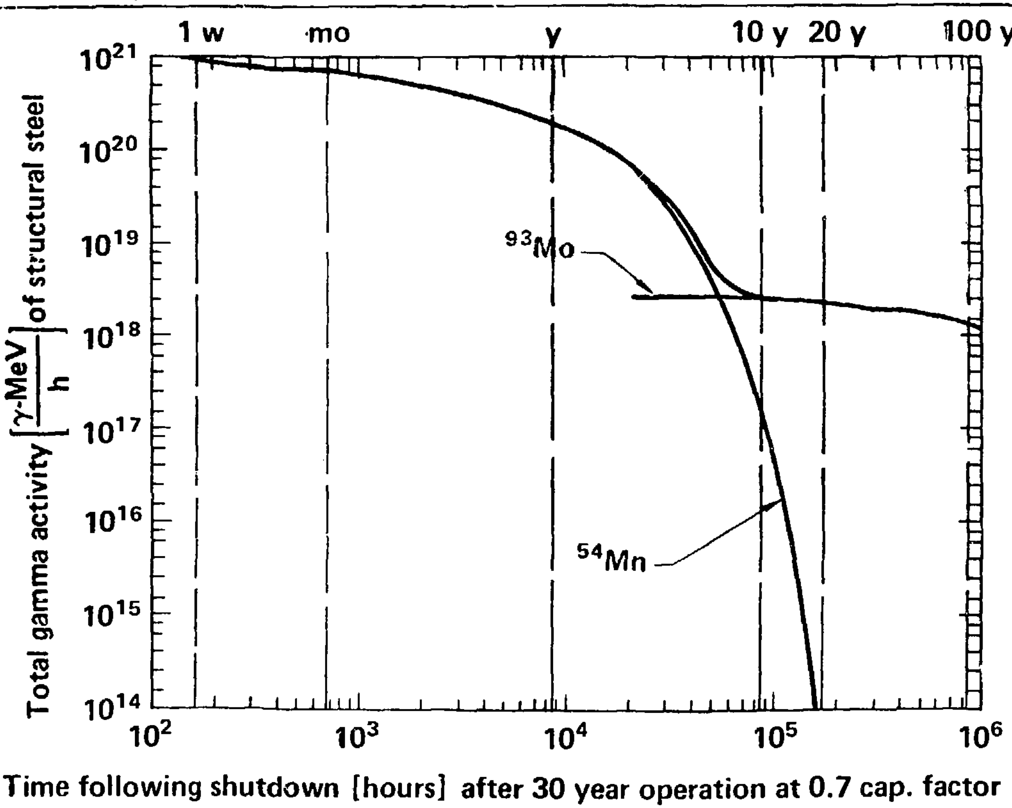

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Figure 6

EXPOSURE RATE [ROENTGENS/sec] AT HYLIFE CHAMBER CENTER AFTER 1 YEAR OPERATION

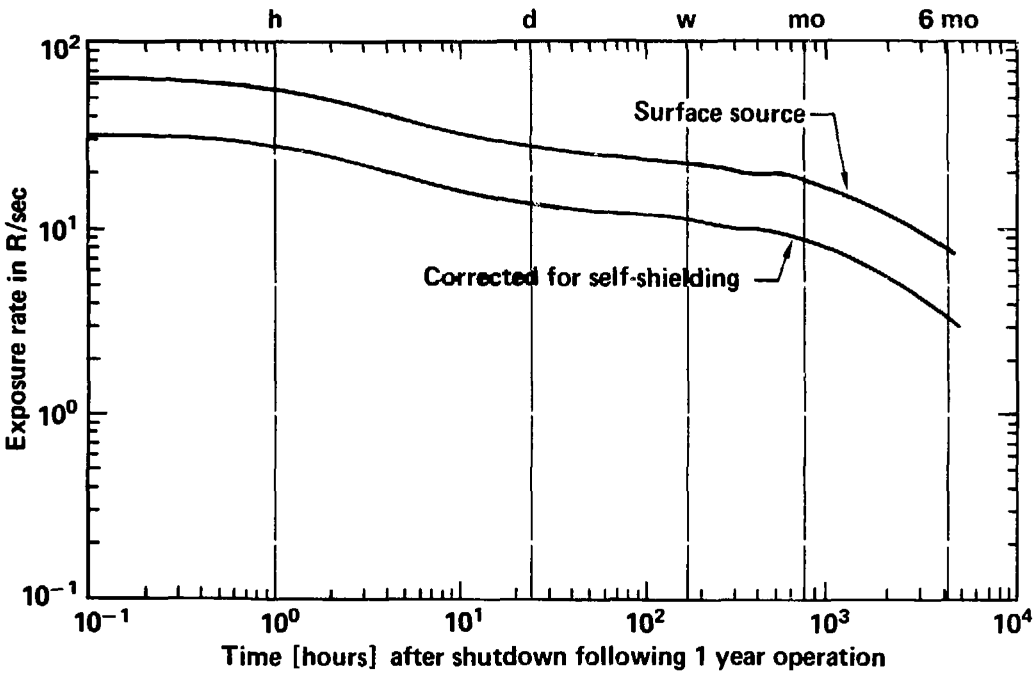

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Figure 7

Exposure rates for a point one meter from the exterior side of the HYLIFE chamber at the midplane and for a point one mete on-axis above the chamber head are given in Figures 8 and 9. Self-shielding and shielding from other blanket structures are included in these results. From Figure 8, we can see that contact maintenance will not be possible at the side of the reactor. Without further shielding, a worker would receive a dose of 1.25 Rad in approximately 3 seconds, even after an unrealistic cooldown period of six months prior to maintenance. Similarly, the exposure rate is down by only a factor of 30 at the top of the chamber; therefore remote systems and additional shielding will also be needed for maintenance or inspection of the head assembly. The HYLIFE chamber is surrounded by a two-meter thick concrete shield located three meters from the chamber wall (see Fig. 2). The gamma exposure rate at a point one meter from the outer surface of this wall is down by a factor of 1.62×10^{11} from the rate at one meter from the chamber wall (Portland concrete with $\rho_{avg} = 2.35$ g/cm^3 assumed). At this exposure rate, hands-on maintenance will probably be possible if structural steel activity is the only source of radiation in the cell. Remote facilities may nevertheless be required if gamma emitters are concentrated in pipe bends or in components of the lithium loops. Concrete shielding above the chamber vault will effectively shield personnel working in that area. None of the foregoing has included streaming in ducts and voids. As more detail is added to the plant design, such considerations will be taken into account.

Exposure rate (R/sec) at a point P 1.0 m from exterior side wall at midplane

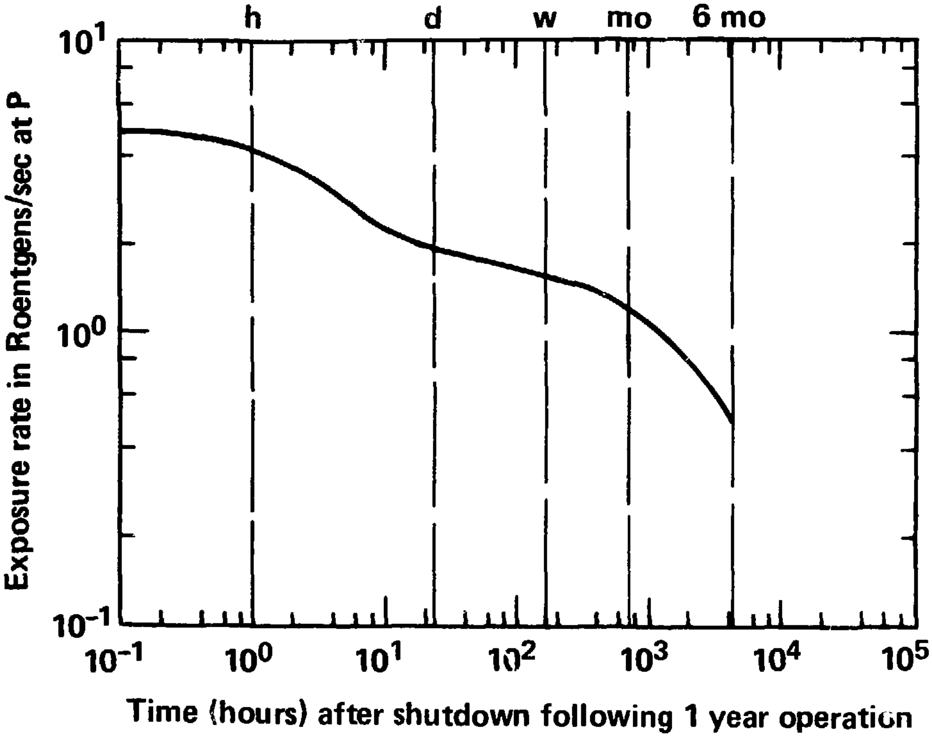

Figure 8

Exposure rate (R/sec) at point P 1.0 m above HYLIFE chamber head on-axis

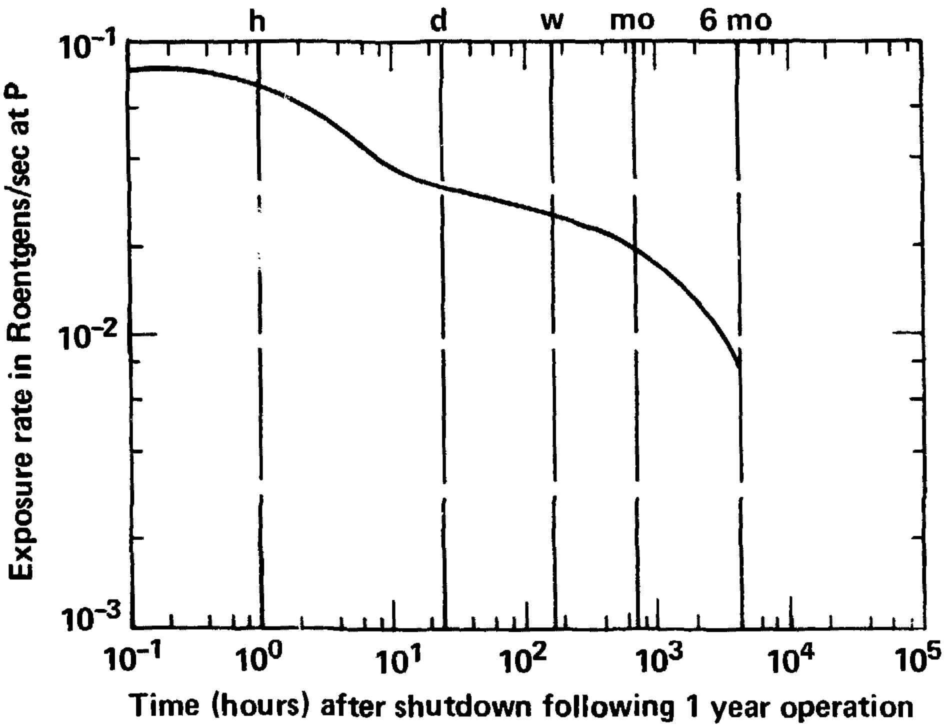

Figure 9

RADIOACTIVITY IN FLOWING LITHIUM

Much has been written about tritium in lithium metal blankets of fusion reactors. Depending on the extraction method chosen, tritium will be present in the circulating HYLIFE power plant coolant at various levels of activity. A realistic concentration range for tritium is from 2 to 10 wppm in lithium. The HYLIFE plant will use tritium removal, processing, and containment technology which has been developed mainly as part of magnetic-confinement fusion research. An effective tritium seal must be maintained during inspection and maintenance operations even if all liquid lithium is removed from the chamber and associated piping. Tritium will diffuse into the steel of the HYLIFE system during normal operation, and it will diffuse back out into the cover gas during maintenance. Operations, remote or contact, on any part of the lithium loops will necessarily include protection from tritium.

In addition to tritum, three other sources of gamma radioactivity in the lithium flow are outlined in Table II. Each of these is discussed briefly below.

Ferritic steel is relatively compatible with lithium metal at the 500°C operating temperature of HYLIFE. Some corrosion will nonetheless occur, and radioactivity will result in the lithium both from radioisotopes corroded with the first-wall steel and from initially stable corrosion products which are irradiated while in the lithium flow. Regardless of which of these two product sources dominates, the activity from corrosion products contributes very little to the total lithium-flow radioactivity. Only 8 mCi of corrosion related activity is present per

Source	Dominant Isotopes Produced		Gamma Energies	Half-Life	Curies/kg of Li (at saturation)
Corrosion products (per appm of parent)	Mn-56, Mn-54, Fe-59 Mo-99, Mo-93		0.89 MeV/decay average	399.8 h (effective)	8.1 E-03
Dissolved Lithium Salts (per appm of parent)	^{82}Br (from tritium extraction)		0.78,0.55,0.62	35.7 h	Pending: cross section data
High-Z Materials from targets (candidate materials listed separately)(data at saturation and assuming no removal of parent by trapping)	Pb	^{203}Pb	0.28,0.40,0.68	52 h	1.2
	W	^{181}W	0.15,0.14	130 d	23.6
	Ta	^{182}Ta	0.1,1.12-1.22	115 d	37.7
	Au	^{198}Au	0.412,0.674	64.8 h	145.4
		^{196}Au	0.345,0.331	6.1 d	103.5

Table II: Gamma Activity in Lithium Flow.

kg of lithium if the flow contains 1 appm of steel alloy atoms. This represents a great deal of corrosion since the lithium flow contains over 500 tonnes of lithium. Compared to other sources of activity, corrosion products are not believed to be of great importance unless concentrated in a lithium cleanup trap at some point in the loop.

A molten-salt technique using three salts of lithium is being investigated as a scheme for tritium extraction in the HYLIFE plant.[6] Bromine from the LiBr used in this process could present a serious source of radioactivity. Quantitative analysis of bromine activation has not yet been accomplished because of a lack of activation cross section data in the appropriate neutron spectrum. However, Br-81 (49.46% abundant) has a 3 barn cross section for thermal neutron capture, and the Br-82 product has a high gamma yield per decay and a half life of 35.7 hours, which indicates a significant impact on short-term maintenance in the coolant loop.

Heavy metals may be used in laser fusion pellets. The activation of these metals could provide the dominant gamma radioactivity in the flowing lithium, as indicated in Table II. The most likely candidate heavy metal is lead. Natural lead is inexpensive, abundant, effective as a preheat shielding material in a fusion pellet; and Pb-206, 207, and 208 have low activation cross sections and relatively innocuous reaction products. Pb-204 (1.48% abundant) will activate in (n,2n) reactions to produce Pb-203 which may build up in the lithium flow to create high levels of activity, especially in heavy metal cold traps used to remove debris from the lithium. Table II presents data comparing various candidate heavy metals. The activity values given are calculated assuming that the metal is allowed to remain in the lithium flow and that saturation activity is reached (i.e., the decay rate equals the production rate). Therefore, these are upper-bound values and should be considered for comparison purposes only. Lead becomes especially attractive if economic isotopic separation of feed lead for fusion pellets is possible. Such a process could reduce transient lead activity levels by over two orders of magnitude. The use of isotopically-separated lead will require recovery and reprocessing systems in the HYLIFE plant. These systems will, in turn, require remote servicing because of short-term high levels from activated lead. A conveyor belt and holdup tank for cooldown of entrapped lead may be designed to allow refabrication processes to be performed with stable lead.

POSSIBLE APPLICATIONS OF REMOTE SYSTEMS

The most important applications of remote systems in HYLIFE operations are for inspection and maintenance during the 30 year plant life. A possible lesser application is for handling and disassembling the vessel and associated components following decommissioning of the plant.

Inspection operations will be normally conducted with the power plant shut down. However, certain inspections such as viewing flanges and welds on piping nozzles at the head of the vessel can be performed during operation. Neutron leakage and secondary gamma radiation from neutron capture in the chamber and shielding will be the important sources influencing design of remote systems for use during full-power operation.

Radiation sources during operation will be defined and analyzed in future publications. Some of the areas for remote system inspections while the plant is shut down are:

- piping, flanges, welds
- chamber interior wall
- injection plates and splash baffle
- beam tube coupling and blast baffles
- pellet injection tube
- pumps and valves
- tritium extraction facility
- lithium clean-up traps.

In designing remote systems for each of these applications, maximum use of existing systems for LMFBR or magnetic fusion reactors will minimize costs.

Maintenance may occur as a scheduled activity or as an unexpected necessity. Flexibility in design of remote maintenance systems should permit their use in either case. Regularly scheduled remote maintenance may be required on:

- the chamber interior and openings
- pellet injection apparatus
- laser beam tube blast baffles (Figure 1)
- lithium clean-up traps
- pumps, casings, and valves
- laser beam optics.

The final optics in the HYLIFE laser beam system are located 60 meters from the fusion chamber. Nevertheless, neutrons streaming down the beam tunnels will activate the final mirror flats and cause damage to the optical coatings. A scheme for protecting the most critical optical surfaces and for replacing damaged final mirrors has been proposed by M. Monsler.[7] His proposed rotary table of final mirrors is illustrated in Figure 10. Remote handling of the activated mirrors may be required. Such a system could be directly coupled to the rotary table, and would consist of a feeder tray and conveyor for removing activated mirrors and inserting new ones. This remote system must be designed to maintain the integrity of the containment structure, which includes the beam tubes and the final optics.

The HYLIFE concept offers a greater promise of material recyclability than any other nuclear power plant. Following a full 30-year service life and subsequent cooldown period, the large quantity of structural steel can be dismantled and recast for further use. The length of the required cooldown can range from as little as 20 years to more than 800 years. Figure 11 illustrates the exposure rate at the center of the chamber following a full service life and long-term cooldown. At times beyond 10 to 20 years, Mo-93 is the only significant gamma-emitting isotope present in HYLIFE steel. We are presently investigating the feasibility of isotopically separating the molybdenum used in the 2 1/4 Cr - 1 Mo steel to reduce the abundance of the Mo-92 and Mo-94 parents of long-term Mo-93 activity. Dramatic reductions in the waiting period before recycling may be possible at relatively little added

FINAL FOCUSING SYSTEM

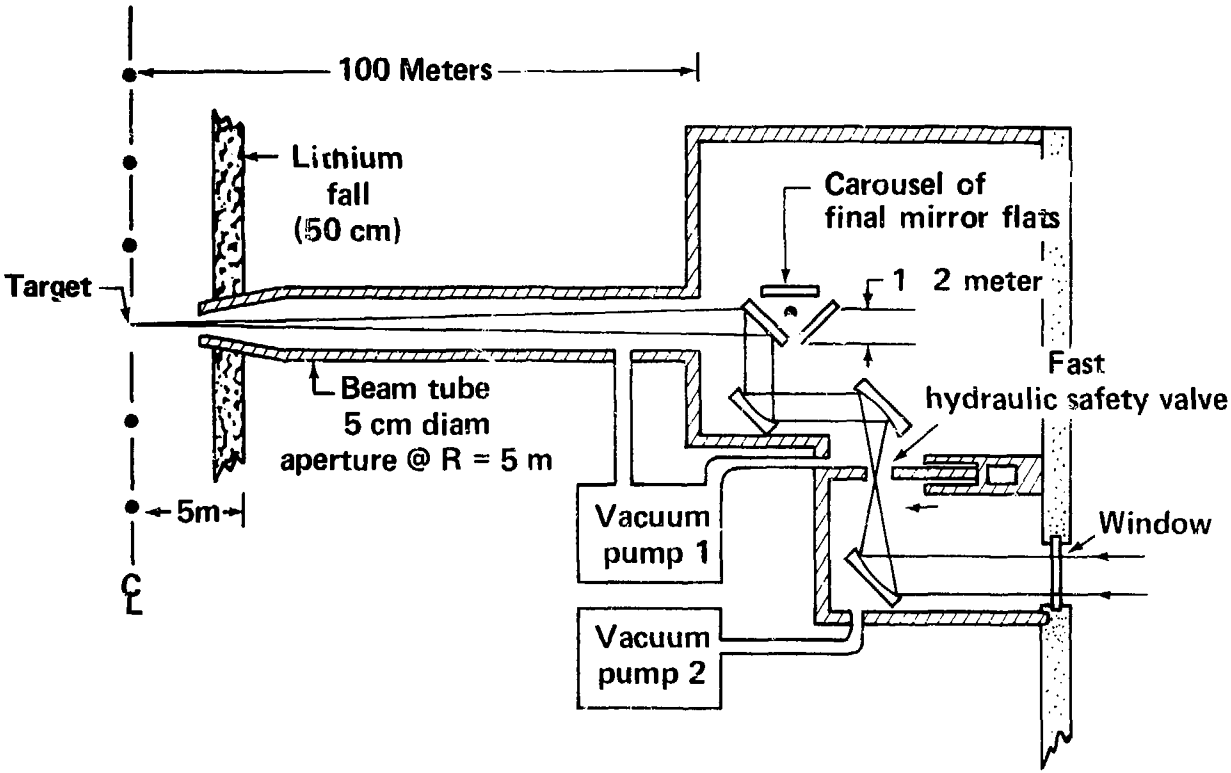

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Figure 10

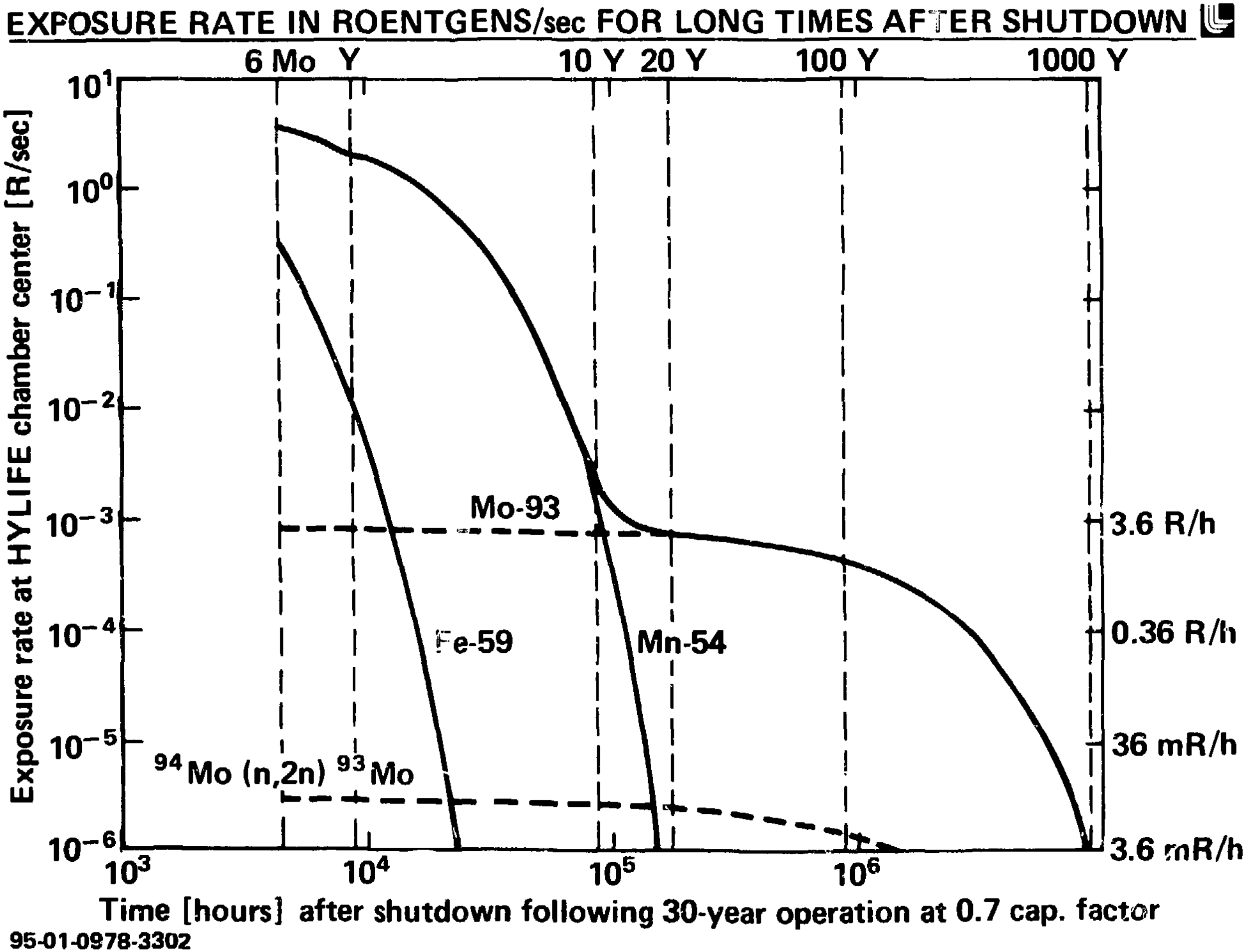
EXPOSURE RATE IN ROENTGENS/sec FOR LONG TIMES AFTER SHUTDOWN
6 Mo
Y
10 Y
20 Y
100 Y
1000 Y
Exposure rate at HYLIFE chamber center [R/sec]
10^1
10^0
10^-1
10^-2
10^-3
10^-4
10^-5
10^-6
Mo-93
Fe-59
Mn-54
94Mo (n,2n) 93Mo
3.6 R/h
0.36 R/h
36 mR/h
3.6 mR/h
10^3
10^4
10^5
10^6
Time [hours] after shutdown following 30-year operation at 0.7 cap. factor
95-01-0978-3302

Figure 11

initial capital cost. However, if the reprocessing is initiated early after final plant shutdown, remote systems may be required to dismantle and transport the activated steel.

CONCLUSION

As the design of the HYLIFE power plant continues, more specific requirements for remote systems will emerge. A fairly complete definition of activated steel radioactivity is now available for shielding, health physics, and remote technology computations. In the future, source terms for leakage neutrons and capture gamma radiation will also be available. Lawrence Livermore Laboratory will work with the nuclear industry to identify, quantify and design those remote systems required by the HYLIFE concept.

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