UCRL- 92012
PREPRINT
CONF-850310--16

UTILIZATION OF FISSION REACTORS FOR FUSION ENGINEERING TESTING

G. A. Deis
L. G. Miller

This paper was prepared for submittal to the
Proceedings of the 6th Topical Meeting on the
Technology of Fusion Energy,
San Francisco, CA, March 3-7, 1985

MASTER

February 8, 1985

Lawrence Livermore National Laboratory

UCRL--92012

DE85 006742

UTILIZATION OF FISSION REACTORS FOR FUSION ENGINEERING TESTING*

G. A. Deis[†] and L. G. Miller
EG&G Idaho, Inc.
P.O. Box 1625
Idaho Falls, Idaho 83415
(208) 526-1800

ABSTRACT

Fission reactors can be used to conduct some of the fusion nuclear engineering tests identified in the FINESSE study. To further define the advantages and disadvantages of fission testing, the technical and programmatic constraints on this type of testing are discussed here. This paper presents and discusses eight key issues affecting fission utilization. Quantitative comparisons with projected fusion operation are made to determine the technical assets and limitations of fission testing. Capabilities of existing fission reactors are summarized and compared with technical needs. Conclusions are then presented on the areas where fission testing can be most useful.

INTRODUCTION

Fission reactors provide one option for performing some of the tests needed for fusion development. One purpose of the FINESSE study[1] was to determine both the usefulness of fission testing in the overall fusion engineering development effort and the areas where fission testing can be best used. Although the value of fission testing depends to some degree on the particular fusion development scenario, the technical and programmatic constraints on fission testing must be examined also to clarify the advantages and disadvantages of fission testing. In this study, we consider only engineering testing (as opposed to materials testing); and we emphasize integrated tests because of their greater impact on overall program strategy.

KEY ISSUES FOR FISSION UTILIZATION

Eight issues are typically cited as technical or programmatic restrictions that limit the usefulness of fission-based testing for fusion engineering development. These issues are listed in Table 1 and are discussed in the following topics. The concerns associated with some of these individual issues (such as power density, lithium burnup, etc.) can be reduced to a limited extent, but for others (such as test volume and availability for testing) the concerns cannot be eliminated. However, even if individual issues can be resolved through test design, multiple effects tests typically show a degraded performance in other areas resulting from these individual solutions. Thus, these issues must be considered as a set, which when considered together may restrict the usefulness of fission testing. We use these eight issues here to focus the analysis and discussion, and to determine the importance of each issue.

Radiation Damage

One of the differences between the "fusion environment" and the "fission environment" is the neutron spectrum. One primary area where the spectrum is known to be extremely important is radiation damage in structural materials. This includes the types of damage and rates of production, and the total amount of radiation damage that can be accumulated. These considerations are discussed here only as they apply to structural materials; damage to solid breeders is discussed under the lithium burnup issue.

There are two primary irradiation damage mechanisms that can result in material property changes: atomic displacements and helium production. Whereas displacement damage occurs over a wide range of incident neutron energy, helium production depends on particular (n,α) reaction cross sections, which generally have high energy thresholds.

---

*Work supported by the U.S. Department of Energy, Assistant Secretary for Research, Office of Fusion, under DOE Contract No. DE-AC07-76ID01570 and W-7405-ENG-48 for LLNL.

[†] Current address: L-544, Lawrence Livermore National Laboratory, P.O. Box 808, Livermore, CA 94550 (415) 423-7533.

Table 1. Key issues in the use of fission reactors for fusion development testing.

Radiation damage:	types and rates
Power density:	magnitude and spatial profile
Lithium burnup rate:	magnitude and spatial profile
Test volume	total of existing test locations
Non-nuclear conditions:	magnetic field, surface heat, particle flux, mechanical forces
Reactivity considerations	
Availability for testing	
Cost	

Therefore, fission tests are expected to produce less helium for equivalent displacement rates. In engineering tests, such as those being considered here, we are primarily interested in observing life-limiting failure modes in a multimaterial, multiple-effect test assembly operating at prototypical conditions (power density). To examine the prospects of accomplishing this objective, we calculated structural radiation damage rates for fission-based blanket submodule tests.[1] From these calculations, we conclude that for the equivalent blanket power density, we expect higher damage rates in the fusion spectrum, as well as much more helium production per atomic displacement. These conclusions duplicate the current understanding of fusion vs fission radiation damage.

Several additional points concerning the use of fission reactors to test for radiation damage follow. First, other materials (e.g., solid breeders or beryllium) are much less sensitive to the differences between fusion and fission spectra, and therefore excellent performance information can be obtained from fission reactor tests on these materials. Second, a number of innovative techniques have been used in the past to overcome the lower helium production rates expected in fission tests. These techniques included the use of the ^{58}Ni(n,α) reaction in nickel-bearing materials or doping with trace amounts of boron or lithium to increase the rate of helium production in the fission spectrum. Third, fission tests will provide a better simulation of damage in structures that are deeper in the blanket (rather than at the first wall) because of moderation in the high-energy-fusion neutron flux. Overall, these three points imply that fission testing is better suited for beginning-of-life testing, where there is less emphasis on material damage, than for middle- or end-of-life testing, where radiation damage may influence blanket-failure mechanisms. Nevertheless, the capability of fission testing to provide various other test conditions simultaneously with some radiation damage testing possibilities is unique and potentially useful.

Power Density/Lithium Burnup Rate

For many of the principal fusion blanket engineering issues, the local power density or its distribution over some volume, is an important factor.[1] To use fission testing to study these blanket issues, two primary concerns must be examined: (1) determine whether or not sufficient power density can be attained, given the neutron fluxes in current fission test reactors; and (2) determine the effect of the spectrum difference between fusion and fission on the power density profile in fission tests. The issue of the lithium-burnup rate is closely related to power density, because lithium reactions are typically responsible for a large fraction of the power density in blankets. Consequently, we will examine the issues of lithium burnup rate and spatial profile together with the power density issues.

Fission testing has two outstanding capabilities: the ability to produce volumetric heating and tritium in situ. No approach other than neutron/gamma heating can bulk heat all materials (metals, ceramics, etc.) simultaneously, which is required for complex engineering tests. The in situ production of tritium is also important and difficult to obtain outside a fission or fusion neutron environment. The capability of providing both bulk heating and tritium production opens a wide range of test possibilities unique to fission testing. To quantitatively address the concerns relating to power density and lithium burnup in fission-based tests, a number of test concepts were developed that provided the bases for physics calculations comparing the performance of the tests with actual fusion operation. Two submodule-scale solid-breeder blanket tests were conceptualized: one for the $LiAlO_2/Be/H_2O$/PCA blanket (Fig. 1) and one for the Li_2O/He/HT-9 blanket (Fig. 2). Both of these concepts are in-core multiple-effect tests, based on one or several blanket unit cells; and, thus, they were intended to represent an intermediate class of test in terms of size and complexity. At the other end of the spectrum, a number of core-side full-module (or slab-module) tests were investigated; and these represent the largest

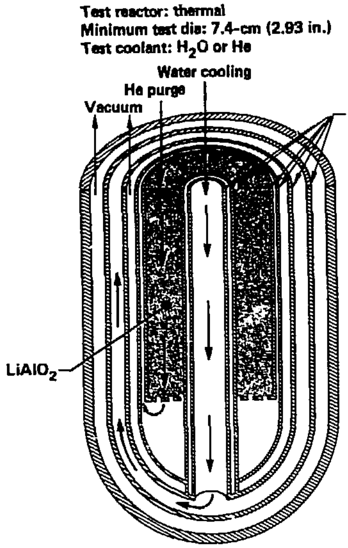

Fig. 1. Submodule test concept for $LiAlO_2/Be/H_2O/PCA$ blanket.

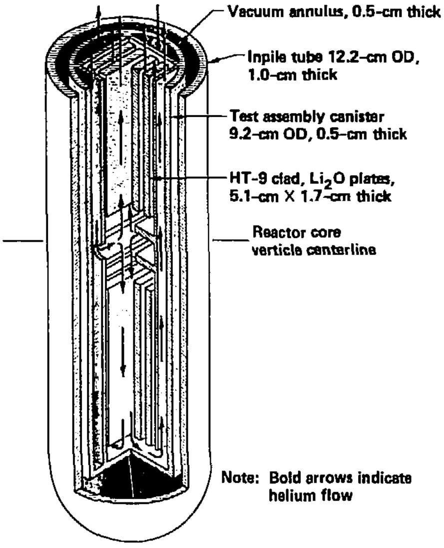

Fig. 2. Submodule test concept for $Li_2O/He/HT-9$ blanket.

and most complex fission-based blanket tests that are of interest. The general concept for these tests is indicated in Fig. 3. The results of the analyses performed on these tests are summarized below; details may be found in Ref. 1.

For the $LiAlO_2/Be/H_2O/PCA$ submodule (unit cell) test, a flat spatial distribution of both power density and tritium production is desired because the test assembly simulates a relatively small portion of the blanket, over which conditions do not change drastically. The neutron physics calculations performed for this test show that 100 W/cm^3 (representing conditions at the front of the blanket) is attained for a total fission neutron flux of 9.1×10^{14} $n/cm^2 \cdot s$ at the outer edge of the $LiAlO_2$ annulus. Although there are many variables to consider, including core loading, this value indicates the general range needed to attain such high power densities; this requirement may, therefore, limit, the number of acceptable reactors. However, as mentioned previously, test power density and size are related, and if the test assembly outer diameter could be increased, the power density would decrease. Scaling could be used, if necessary, to adapt the test to large, lower-flux reactors. For the 100 W/cm^3 power density operation, the average tritium production rate is 1.1×10^{14} $T/cm^3 \cdot s$, or approximately 13% burnup per year, which is typical for high-power-density areas in the blanket.

For the Li_2O submodule test, the objective is to take advantage of the axial power variation in an inpile tube-type test to simulate the power variations with depth into a fusion blanket. For this reason, radial variation within the test must be minimized. Figure 4 shows the radial profiles of power density and tritium breeding rate. Although the profile is strongly peaked, the test design takes advantage of this fact. By incorporating multiple plates, which are suitably wide, the center area of the middle two plates is essentially free from any nonuniformities or end effects.

In the reference $Li_2O/He/HT-9$ blanket, the power density in the Li_2O varies between 43 and 3.3 W/cm^3. Table 2 lists the total neutron flux required at the edge of the test to duplicate the above values. Table 2 also shows the comparison between the tritium production rates in the fission and fusion cases, where the power density is matched at 43 and 3.3 W/cm^2. For this test configuration and at the highest power density, the tritium production rate is higher by a factor of two in the test. The tritium production is equivalent to the fusion case at the lowest power density. The increased tritium production is probably an advantage because it implies accelerated damage in the ceramic. However, increased

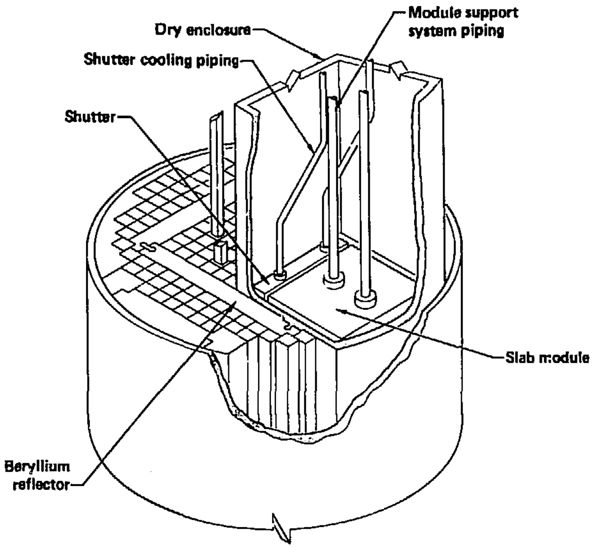

Fig. 3. Cutaway view of a slab-module fission-test configuration

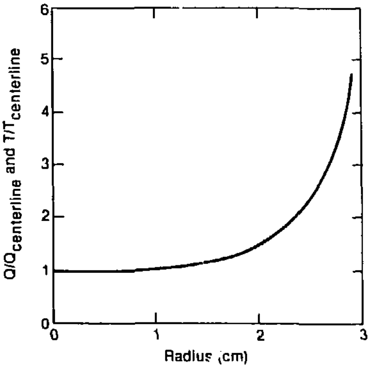

Fig. 4. Normalized power density and tritium production profile in Li_2O/He/HT-9 submodule test.

Table 2. Li_2O/He submodule performance parameters.

Fusion and fission power density[a] (W/cm^3)	Total neutron flux at edge of test (n/cm^2•s)	Tritium production (T/cm^3•s)	
		Fusion	Fission
43	2.1×10^{15}	2.1×10^{15}	3.1×10^{13}
3.3	1.6×10^{14}	2.4×10^{12}	2.4×10^{12}

[a] All results for fission test normalized to same power density as fusion case. All calculations based on "uniform conditions" that exist within the center 4-cm diameter of test (^6Li self-shielding peak ignored).

tritium production could also change the chemistry or thermodynamics of tritium recovery and, therefore, its effect must be studied closely.

Three slab-module test concepts have been investigated: one each for the Li_2O/He/HT-9, $LiAlO_2$/Be/H_2O/PCA, and Li/Li/V concepts. In all cases, we assumed that an entire, full-scale blanket module is placed against a face of a thermal reactor core. The physics model for the module was identical to that used for reference (fusion source) calculations. To account for the strict containment requirements in fission tests, we modeled 2 cm of 316-SS between the core and the module. In addition, some cases were run with a 0.15-cm-thick cadmium filter to examine the filter's effects on the power density and tritium production profiles. The results of these calculations for the Li/Li/V module (Fig. 5) are characteristic of those for the other concepts. In Fig. 5, the regions shown are in order as follows: first wall, toroidal cooling channels, second wall, poloidal manifold, and reflector. The data have been normalized to produce power densities equivalent to 1 MW/m^2 fusion operation in the blanket, rather than at the first wall. The good overall agreement between operation with fusion source and with fission source is obvious. However, the effect of the lower-energy fission spectrum is also apparent in the local peaking in both power density and tritium production at the front of the blanket. In this particular case, this local peaking could be an asset if the average power density in the toroidal channels were increased. In other cases, particularly solid breeder blankets, the power peaking may be less desirable. In those cases, a thermal neutron filter may be required. Calculations show that a cadmium filter is helpful, but in certain cases a 1/v absorber, such as boron, ^{6}Li or ^{3}He would probably be preferable. The effect of these filters can be seen in Fig. 5, if the Li-bearing toroidal channel is considered to be a filter between the reactor and the poloidal channel: note the excellent agreement between fission- and fusion-source profiles in the poloidal channel.

Overall, our conclusion based on the foregoing discussion is that fusion-relevant spatial profiles of power density and tritium production can be produced in both submodule and slab-type fission-based tests. In most cases, local peaking resulting from ^{6}Li self-shielding can be expected. This condition can, in many instances, be used to advantage. In cases where local peaking cannot be used constructively, neutron spectrum filtering can be used to remove the lowest-energy portion of the spectrum and thereby reduce peaking. This process may increase the total flux required for prototypical operation.

The magnitudes attainable in power density and tritium production are two primary fission testing concerns that have not been addressed. In the data presented previously, calculations for fission tests were normalized to produce power densities similar to 1 MW/m^2 fusion operation. The issue, then, is: can the required source fluxes be attained. Table 3 summarizes the total fluxes required at the surface of the test assemblies for both submodule and slab-type tests. These values, though high, are probably attainable in most cases, as discussed in the following section. An important point to consider is the difference between the usual flux in the test location (unperturbed) and the flux in that location when the test assembly is in place.

Figure 6 shows this flux depression effect for slab-module tests as a function of reactor core thickness. The plotted values are equal to the fraction of the unperturbed flux that is lost when the test module is installed. Although the flux depression is not a strong function of reactor core thickness, the overall magnitudes are quite high. This observation leaves a concern that the required fluxes may

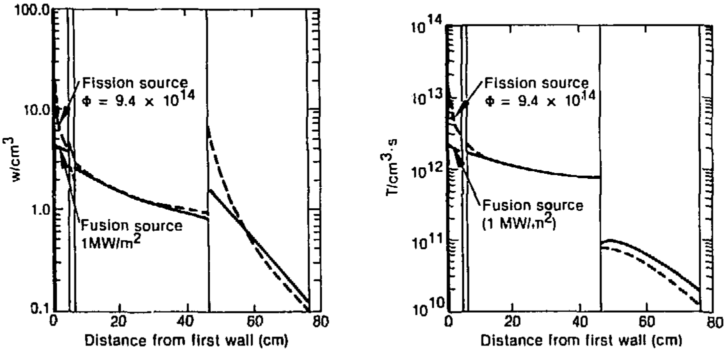

Fig. 5. Power density (a) and tritium production (b) profiles in fission slab-module test for the Li/Li/V blanket

Table 3. Flux required at face of test assembly to simulate power density at front of fusion blanket at 1 MW/m^2

Type test	Blanket concept	Neutron Filter	Flux[a] (cm^{-2} s^{-1})
Slab[b]	Li_2O/He/HT-9	--	1.4×10^{15}
		Cd	1.5×10^{15}
Slab	Li/Li/V	—	9.4×10^{14}
Slab	$LiAlO_2$/Be/H_2O/PCA	--	9.8×10^{14}
		Cd	8.7×10^{14}
Submodule[c]	Li_2O/Be/HT-9	--	5.1×10^{14}
Submodule	$LiAlO_2$/Be/H_2O/PCA	--	2.1×10^{14}

[a] Water-moderated, plate-fueled fission reactor assumed.

[b] Core-side.

[c] In-core.

be difficult to attain when flux depression is taken into account. It is extremely important to observe, however, that the flux depression values in Fig. 6 depend on the fission core configuration. Actually, the likelihood is that elements with higher fuel loadings would be used near the test modules to help flatten the flux profile in the core edge. Therefore, the information in Fig. 6 probably represents upper-limit values.

Overall, the above observations indicate that adequate (1 MW/m^2 equivalent) power densities and tritium production rates can be attained in fission based tests, although the required fluxes are high. Considering the flux depression effect, even higher unperturbed flux will be required in the test location. Though attainable, this requirement will impact the number of reactors that are capable of being used for fission-based testing.

Test Volume

The test volume available in fission reactors has been an area of some concern. Largely because of the containment requirements (resulting from the reactive materials, high temperatures, and high pressures), fusion blanket tests typically require a rather large test space even for tests of simple configuration. Thus, test locations must be located that are both large enough and have sufficient flux. These test sites must also exist in sufficient quantity to satisfy the needs of the fusion engineering program. From the testing needs defined in FINESSE,[1] we find that hundreds of fission-based engineering tests could be of interest to the fusion program.

To address these concerns, we reviewed the published specifications of the largest and highest-flux U.S. and foreign test reactions. The data obtained for submodule tests in U.S. reactors (and for U.S. plus foreign reactors) are summarized in Table 4. Each entry in Table 4 is the number of test locations that could be used to conduct a test of a given size at a given flux; the entries also include larger and higher-flux locations because, for instance, a small test could be conducted in a large hole. In developing submodule tests for FINESSE, the smallest test size devised was 7.4-cm outside diameter; this is probably the

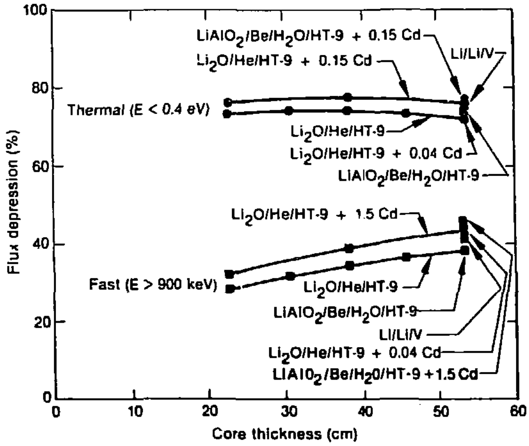

Fig. 6. Flux depression as a function of core thickness for slab-type fusion-blanket tests.

Table 4. Numbers of existing acceptable in-core test locations in both U.S. and U.S. and foreign reactors

Minimum required flux ($n/cm^2 \cdot s$)	Test assembly maximum dimension (cm)				
	5	7.5	10	12.5	15
5×10^{12}	180(315)[a]	119(168)	33(79)	16(45)	2(27)
5×10^{12}	167(292)	106(145)	30(66)	15(44)	1(26)
5×10^{12}	49(69)	13(30)	13(30)	10(27)	0(16)
5×10^{12}	40(40)	4(4)	4(4)	1(1)	0(0)

[a] Numbers in parentheses are for U. S. and foreign reactors.

minimum credible size for any engineering-type test. In addition, neutron fluxes in the range of 10^{14} $n/cm^2 \cdot s$ are required; this is typical of the flux required for any engineering test. These two considerations limit the total number of acceptable locations to less than 100 for U.S. and foreign reactors combined. Larger test assembly size and higher flux requirements (especially important) will further limit the number of useful reactor locations.

For slab-type tests, we found a scarcity of suitable locations. The data in Table 5 shows that with current reactors, reasonable slab-module tests at prototypical conditions are not possible without modifications. All of the previous considerations, however, are based on the published specifications of existing reactors. If reactor modifications are considered, the situation can change. Relatively minor modifications could increase the availability of larger test locations (both core-side and in-core). Modifications could also improve test fluxes, although the improvement would not be as much as with increased size. These considerations are extremely facility-specific and also somewhat speculative (in terms of quantitative impact)--one example of particular interest concerns the possibility of conducting slab tests in the Oak Ridge Research Reactor (ORR). Currently, slab tests approximately 68 x 75 cm could be operated at total fluxes up to 3×10^{14} $n/cm^2 \cdot s$. With an increase in allowable reactor power (which could entail additional plant equipment such as heat exchangers) and careful management of the core loading, the test-area flux could be more than doubled, which would probably permit acceptable test conditions in the module.

In summary, we conclude that the number of useful test locations in fission reactors is somewhat limited. There may be an adequate number of in-core positions, particularly if reactor modifications are considered. There are few truly useful existing slab-test locations, primarily because of flux (as opposed to geometry) requirements. However, modifications could improve this situation, and in fact, it appears that at least one acceptable location could be produced at the ORR.

Table 5. Numbers of existing acceptable slab-test locations in U.S. and U.S. and foreign reactors

Minimum required flux ($n/cm^2 \cdot s$)	Test assembly maximum dimension (cm)				
	25	50	75	100	150
5×10^{13}	7(11)[a]	1(4)	0(2)	0(1)	0(1)

[a] Numbers in parentheses are for U.S. and foreign reactors.

Non-Nuclear Conditions

Considering all testing issues, neutrons are probably the single most important environmental factor. Nevertheless, other non-nuclear factors can be equally or more important than neutrons for individual issues. Particular effects of concern include mechanical forces, surface heat flux, magnetic field, and particle flux. The application of mechanical forces during irradiation is standard practice in many in-reactor tests such as irradiation-creep tests. It is usually accomplished by small gas cylinders with leads routed outside the reactor where the pressure can be controlled. Similarly, no fundamental problem exists in supplying a surface heat flux. Many in-reactor experiments incorporate some type of electrical heater to maintain temperature control. To produce magnetic fields of high enough intensity (1 Tesla or more) and in large enough volume to be of interest, large magnets are usually required. In addtion, ensuring that the stray field (or return flux) will not exert transient or steady-state forces on reactor components will be difficult. Implementing magnetic fields within fission tests may therefore be difficult. Finally, no acceptable method of producing a first-wall-like particle flux in the fission reactor environment has been developed to date. Use of a ^{3}He layer would produce some ions and heat, but at levels below those of interest in engineering testing.

Reactivity Considerations

Because fusion-blanket test assemblies will be excellent neutron absorbers, the effect of the tests on the reactor's reactivity balance is an important consideration. We have performed calculations for both submodule and slab-type fission tests to determine the net reactivity worth of the test assemblies described earlier. For the submodule tests, we found that the reactivity worths were -6.2\$ for the $LiAlO_2/Be/H_2O/PCA$ test, and -7.1\$ for the $LiO_2/He/HT\text{-}9$ test. These values, when compared with an average control-rod worth of +2.50\$, are not excessive. For the slab-type tests, we found that the reactivity worth of the test assembly depends strongly on the thickness of the reactor core, as shown in Fig. 7. The implication is that small cores (less than approximately 30-cm thick) will have serious difficulty in supplying the necessary reactivity. Large cores, greater than 50-cm thick, can certainly accommodate tests. Medium cores (30-to-50-cm thick) can probably accommodate slab tests, but it is likely that some modifications (such as higher fuel loading or rearrangement of control rods) will be necessary.

In summary, reactivity (criticality) considerations do not seem to be a serious problem for submodule tests. For slab tests, reactivity requirements will probably restrict the choice of useful reactors to those with a core thickness greater than 30 cm.

Availability for Testing

The availability of facilities is essentially a programmatic issue; information on this issue was obtained from a written survey of major U.S. test reactors. In all responses, facility operators indicated that their reactors either were available or could be available given proper programmatic priority. In addition, current plans indicate that most facilities will to continue operation for the indefinite future; the exceptions to this are: EBR-II, projecting only 10 years of operation; and PBF, projecting only one year. Note also that the ETR was mothballed several years ago. Taken together, all this information seems to indicate a slow downward trend in the availability of fission reactors for testing. This trend appears to be slow enough that it could be reversible if programmatic issues so dictated.

Cost

Although no specific effort has been made to compare the cost of fission tests with those of fusion tests, three main points can be made. First, equivalent test hardware for fission and fusion tests will have equivalent cost because the design requirements for both will be similar. Second, the cost of the facility operation will be much higher for a fusion test device than for a fission test reactor. Third, fission test capabilities, some highly developed, exist and are available now; the construction of a new facility may not be necessary. Consideration of these points leads to the conclusion that fission testing will be less costly than fusion testing. However, each

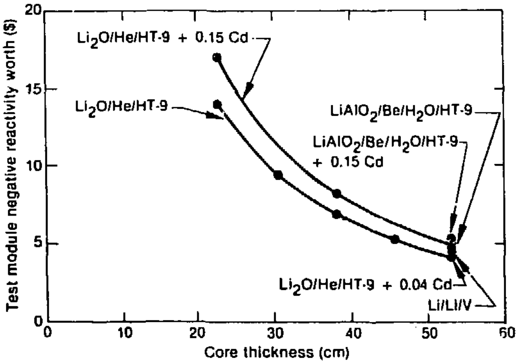

Fig. 7. Slab-test module negative-reactivity worth as a function of fission core thickness.

experiment needs to be considered on a cost/ benefit basis.

CONCLUSIONS

Although the amount of fission testing that is used in fusion development will depend on the development scenario chosen and on the cost and benefits of other testing options (point neutron sources, fusion test devices, etc.), general guidelines can be developed from the preceding discussion. In particular, fission testing is well-suited for conducting many multiple-effects tests, which generally require a number of significant environmental factors, but not complete act-alike performance. Because the FINESSE study[1] found that complete act-alike performance is extremely difficult to attain even in fusion test devices, these multiple-effects tests will represent the bulk of the engineering development effort. The primary role of fission testing will probably be in submodule scale tests because a number of acceptable test locations exist and because the simulation requirements are somewhat relaxed for tests of this type. Full-module slab tests in fission reactors will be useful primarily for beginning-of-life performance evaluations and to allow early identification of some radiation-related synergisms. In general, fission testing will probably be somewhat more useful for solid-breeder blankets than for liquid-metal blankets. This is because the most critical issues for solid-breeder concepts (heat transfer and tritium release) match the capabilities of fission testing (bulk heating and in-situ tritium production) better than the most critical issues for liquid-metal blankets (magnetohydrodynamics (MHD) and corrosion).

The usefulness of fission testing is limited in three main areas. First, difficulties exist in trying to include all of the non-nuclear conditions that may be of interest. Second, the differences in spectra between fusion and fission leads to difficulty in simulating structural radiation damage and leaves doubts concerning radiation-related synergisms. Finally, fission testing is currently limited in the total number of acceptable test locations, particularly slab-test locations. These limitations apply primarily to component testing and do not seriously reduce the usefulness of fission testing for multiple-effects tests.

Overall, fission testing *can and should* be an integral, useful part of the fusion engineering program. Although fission testing cannot completely replace or eliminate the need for fusion testing (except for extremely high-risk development scenarios), it can address many critical fusion testing needs to various degrees. The principal advantages of fission testing is timeliness (it is available now) and cost-effectiveness (no new facility construction required). In the final analysis, each fission experiment or fusion development scenario considered must be evaluated on a cost/risk/benefit basis; in this context, fission testing is less costly and lower risk than fusion testing, but also has less benefit. We conclude, however, that considerable data (even though imperfect) on critical fusion engineering issues can be acquired by testing early and in existing fission facilities--this considerable benefit should not be overlooked.

ACKNOWLEDGMENT

The contribution of the University of California, Los Angeles, Reactor Physics Group (M. Youssef and K. Shin) in performing the submodule test calculations is gratefully acknowledged.

REFERENCES

1. M. ABDOU et al, FINESSE Interim Report (Draft), University of California, Los Angeles UCLA-ENG-84-30 (October 1984).