Use of the Fast Flux Test Facility for Tritium Production

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This report provides the results of a JASON review of the technical feasibility of using the Department of Energy's (DOE's) Fast Flux Test Facility (FFTF) to generate tritium needed for the enduring United States' nuclear weapons stockpile.

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Contents

1 EXECUTIVE SUMMARY: FFTF FOR TRITIUM PRODUCTION

1.1 JASON Task

This report provides the results of a JASON review of the technical feasibility of using the Department of Energy's (DOE's) Fast Flux Test Facility (FFTF) (Hanford, Washington) to generate tritium (T) needed for the United States' nuclear weapons stockpile.[1] We read two summary reports on this subject, one written by The Office of Nuclear Energy, Science and Technology [1] and the other by The Defense Programs Tritium Office [2] (both of the DOE); we received detailed technical briefings on July 15 by Westinghouse Hanford Company (WHC) scientists and engineers and by a scientist from Argonne National Laboratory (ANL); and we reviewed detailed technical reports provided by WHC and ANL [3],[4],[5] and portions of still another [6], as well as other material provided by WHC in response to some of our specific questions. Background information and some of the concerns of the DOE with the proposed FFTF mission were also included in the July 15 briefings.

[1] Some of the specifics of the operation of the FFTF, a nuclear reactor which is fueled with a mixture of PuO_2 and UO_2 (known as "mixed oxide", or MOX, fuel) and cooled by liquid sodium, are provided in the main text of this report. Key features are as follows: the full rated power is 400 MW (thermal); the portion of a full power year that operation is normally possible, called "capacity factor," is limited to about 75% principally because of refueling time; the plutonium portion of the fuel (mostly the isotope ^{239}Pu) generates almost all of the neutrons needed both to sustain the fission chain reaction (and produce the power) and to breed T by reacting with the lithium isotope, ^{6}Li; the uranium in the fuel (virtually all the isotope ^{238}U) provides a very small percentage of the reactor power and neutrons. The T-breeding reaction is $n + {}^{6}\mathrm{Li} \rightarrow \mathrm{T} + {}^{4}\mathrm{He} + 4.8$ MeV.

The specific charge to us for this review was as follows:

"The Tritium Management Board asks the JASONs to:

1. Review and resolve, or
2. identify the steps necessary to resolve, with cost estimates;

the schedule, technical, and risk issues to determine the maximum capacity of the FFTF to produce tritium."

1.2 Findings and Conclusions

The maximum credible T production rate of FFTF is 2 kg per year if the reactor runs at its full rated power and maximum demonstrated capacity factor. Once restarted, ramping the T production rate of FFTF up from 1 to 2 kg per year over several years will involve increasingly demanding technical developments and safety issues. These and other findings and conclusions are discussed in the following eight points, and are supported with more detail in the body of this report.

1. The technical path to restarting the FFTF, operating it close to its full 400 MW_t and 75% capacity factor rating, and producing approximately 1 kg T per year, is straightforward. It appears that there are no significant technical issues in the way of restarting FFTF from its present condition. Production of 1 kg T per year requires simply replacing the Inconel reflector assemblies (currently positioned around the fueled core of the reactor) with T-producing $LiAlO_2$ "target" assemblies. We have high confidence that this T production rate can be achieved and sustained. In order to produce T at this rate (or higher) for more than about 18 months, new MOX fuel must be fabricated. The Fuels and

Materials Examination Facility (FMEF), which is co-located with the FFTF, can be configured to supply both the necessary fuel and target assemblies for the FFTF.

2. In order to achieve a T production rate of 1.5 kg per year, it will be necessary to demonstrate that $LiAlO_2$ target assemblies can be operated in the fueled portion of the FFTF reactor core ("in-core assemblies") as well as in the former reflector region ("ex-core assemblies"). This production rate also requires an increase in the percentage of plutonium in the reactor fuel relative to the uranium from a mixture close to 30/70 to about 40/60 in order to sustain the fission chain reaction in the face of neutron losses to the lithium. The resulting changes in the power production distribution in the core have possible safety implications which will require further analysis and experiments. Before 1.5 kg per year T production can begin, careful testing of the Pu-enriched MOX fuel and of an in-core $LiAlO_2$ target assembly in the FFTF will be necessary while it is operating in the 1 kg T per year production mode. However, we do not consider this required development to be technically challenging, and we are reasonably confident that FFTF can achieve a 1.5 kg per year T production rate.

3. The maximum possible T production per year that FFTF can achieve is determined by its rated thermal power, 400 MW; its capacity factor, 75%; the fact that Pu is its most important fuel component; and the range of neutron energies present in the reactor. A simple calculation using this information, which is detailed in Section 2.4, gives a maximum credible *production* rate of T of 2 kg per year for the FFTF. The actual amount of T that can be delivered to a user is reduced from the production rate because of losses in the separation process (expected

to be small) and because T decays at a rate of about 5.5% per year.

4. In order for FFTF to achieve close to the maximum T production rate of 2 kg per year, not only must the reactor run at full power at least 75% of the year, but additional modifications must be made to the reactor beyond those required for the 1.5 kg per year case. The $LiAlO_2$ target assemblies will have to be replaced by Li_2O, especially to maximize in-core production of T. This, in turn, will require a further increase in the Pu fuel fraction to about 50%. The technical developments needed to use both the Li_2O target assemblies and the 50% enriched fuel do not appear to present high technical risk given existing data. However, such modifications of both the fuel and target assemblies introduce additional safety issues which will have to be carefully analyzed and then rigorously tested in the FFTF while it operates in a 1.5 kg per year production mode before safe and reliable operation can be anticipated with confidence. We find a production rate goal of 2 kg per year to be credible. It is consistent within a few percent with independent core design calculations using different realistic core configurations carried out by WHC and ANL scientists. While we have concluded that there are no technical "show stoppers," everything will have to work up to full potential without a hitch to achieve the 2 kg per year goal on the proposed schedule (by 2005). Extensive detailed analyses which show that potential "worst case accidents" will not jeopardize public safety will also be required. A production rate beyond this level would involve changes to the core of the reactor that might compromise its safe and reliable operation (see Section 2.4).

5. Analysis of previous operations of the FFTF plus long experience with neutron irradiation effects in other reactors suggest that one can be

confident in extending the operating lifetime of the FFTF by 20–30 years beyond the 10–20 years for which its components were originally certified. However, we have not made a detailed analysis on which to base an accurate prediction of the maximum lifetime. We note that recertification of all components need not be completed before restart because FFTF operations so far have totalled the equivalent of only about 7 full power years.

6. There is no major difference between the two cost estimates for FFTF restart and life-cycle operations for T production in the two DOE reports [1],[2]. To summarize, the cumulative cost up to initial T production will be \$300–500M; the 30 year life cycle total cost estimates are in the \$3–4B range. The main difference between the two DOE reports is in their confidence that a production rate higher than 1.5 kg per year can be achieved because of the necessary technical developments for the higher production rates. The two major items are development and testing programs for the Pu-enriched MOX and Li_2O assemblies. The estimated costs in the two DOE reports for these development and testing programs are different, but each one is well under \$100M. This is the extra money (in addition to the restart and operational costs) that will have to be spent to completely resolve the major disagreement between the two DOE reports, namely the high vs low confidence levels of reaching the 2 kg per year maximum T production rate.

7. If DOE chooses to go forward with a T production mission for FFTF, restarting it in a timely manner and assuring timely completion of the development and testing of the Pu-enriched MOX fuel and Li_2O target assemblies for the highest production rate, must become a priority program for several organizations, not just WHC. DOE will have to

call upon resources from Hanford, from ANL and other DOE laboratories, and from DOE headquarters on a high priority basis to complete the environmental, safety and technical analyses, and all the associated regulatory processes that must precede restart.

8. A decision to restart FFTF to produce T must recognize that this facility can contribute substantially to but cannot fully meet U.S. T needs. Currently predicted requirements for T for the U.S. nuclear weapons stockpile a decade and beyond in the future exceed a steady production rate of 2 kg per year.

1.3 Concerns

A. The schedule for initial T-production and ramp-up depends upon completion of a great deal of paperwork, public hearings and the like on environmental and safety issues. (Issues likely to raise public concerns about safety are discussed in Section 5.) Both DOE organizations' reports [1],[2], imply that initial T production is possible in 4–5 years, including completing all paperwork, fulfilling regulatory requirements and renegotiating the agreement on FFTF shutdown among EPA, DOE and the State of Washington ("the Tri-Party Agreement"). Assurance that 2 kg per year of T can be produced requires a development and testing program that cannot be completed until all necessary preliminaries are concluded and the FFTF is back in operation and producing T at the 1–1.5 kg per year rate. In view of the significant testing requirements, as well as the formidable bureaucratic barriers, we are very concerned about prospects of actually achieving a 2 kg per year

T production rate by 2005. Such a schedule will be difficult to keep. However, on the positive side, we note that the necessary development and testing program can be started using the Advanced Test Reactor (ATR) at Idaho Falls. Furthermore, the possibility of producing as much as 300 grams per year of T at ATR [7] could allow some slippage in the T production schedule necessary to meet military requirements.

B. The long-term fuel cycle proposed for FFTF depends on at least two major policy decisions: 1) Pu pits from disassembled warheads must be made available to produce the MOX fuel for FFTF; and 2) the U.S. must accept storage and ultimate disposition of spent MOX fuel containing a high percentage of Pu, which would require considerable dilution with depleted uranium or perhaps reprocessing of the highly reactive spent fuel containing nearly one ton of PuO_2 that will be removed from the reactor annually. At 2 kg per year T production rate, the spent fuel contains $\sim$ 40% Pu by weight, and this Pu will be $\sim$ 90% Pu^{239}.

2 BACKGROUND

2.1 The Need for Tritium and the Record of Decision

With the permanent shut-down of the K-reactor at Savannah River, DOE no longer has a facility to produce the T needed for the U.S. nuclear weapons stockpile. As a result of the START I and START II treaties, our stockpile has decreased in number substantially, significantly decreasing the need for T for these weapons. However, since T undergoes radioactive decay with a half life of 12.3 years, i.e., a decay rate of about 5.5% per year, it will be necessary to have T production capability early in the next century. (For force limits under START I, this date is 2005.) Alone among existing DOE-owned facilities, the FFTF is capable of producing a major fraction of the established T requirements, perhaps as much as 2 kg/year. However, according to present policy on maintaining T for the weapons stockpile, a long term average production rate exceeding 2 kg/year by a significant margin will be needed.

Present U.S. policy on developing T production capability for the future is set forth in the Record of Division (ROD) dated December 12, 1995. The DOE is moving forward with the design of a special purpose accelerator, *and* is considering the possibility of T production with a light-water reactor. In 1998, one or the other of these paths will be selected as the primary one according to the ROD. If the FFTF is to be a viable competitor among possible T-producing facilities, a new or amended ROD is needed immediately and by 1998 we must have confidence that FFTF can deliver the necessary T to the stockpile, presumably in combination with one or more other sources.

2.2 Brief Technical Description and Status Report of the FFTF

The FFTF is a 400 MW_t sodium-cooled, fast-neutron flux reactor plant designed specifically for irradiation testing of nuclear reactor fuels and materials for liquid metal fast breeder reactors. It is characterized by a more energetic neutron energy spectrum than the light-water reactors (LWRs) that constitute almost all of the reactors in operation in the U.S. today. That neutron energy spectrum is the basis for calling the reactor a "fast-neutron" or "fast-flux" reactor, or simply a "fast reactor." It is also a benefit for producing T when compared with using a reactor moderated and cooled by ordinary water, i.e., an LWR. This is because the number of neutrons released per neutron absorbed in a nucleus of the reactor fuel (uranium or plutonium) is higher for fast neutrons than it is for "thermal" neutrons such as are present in an LWR. As a result there are about twice as many neutrons per fission available to generate T by the (n,T) reaction, $n + {}^6Li \rightarrow T + {}^4He$ (with an energy release of 4.8 MeV) in a fast reactor than in an LWR. This translates to a T production rate per unit of thermal power that is about twice as big for the FFTF relative to an LWR.

Under normal operation conditions of the FFTF, mixed oxide fuel (MOX) with an enrichment of 20–30% Pu was fabricated and inserted in the reactor core. A possible core layout for materials testing [5], consisting of 73 "driver" assemblies containing mixed oxide fuel, nine control assemblies, and nine in-core experimental locations, is shown in Figure 2-1. This core is surrounded by two to three rows (108 assemblies) of Inconel reflector assemblies (the

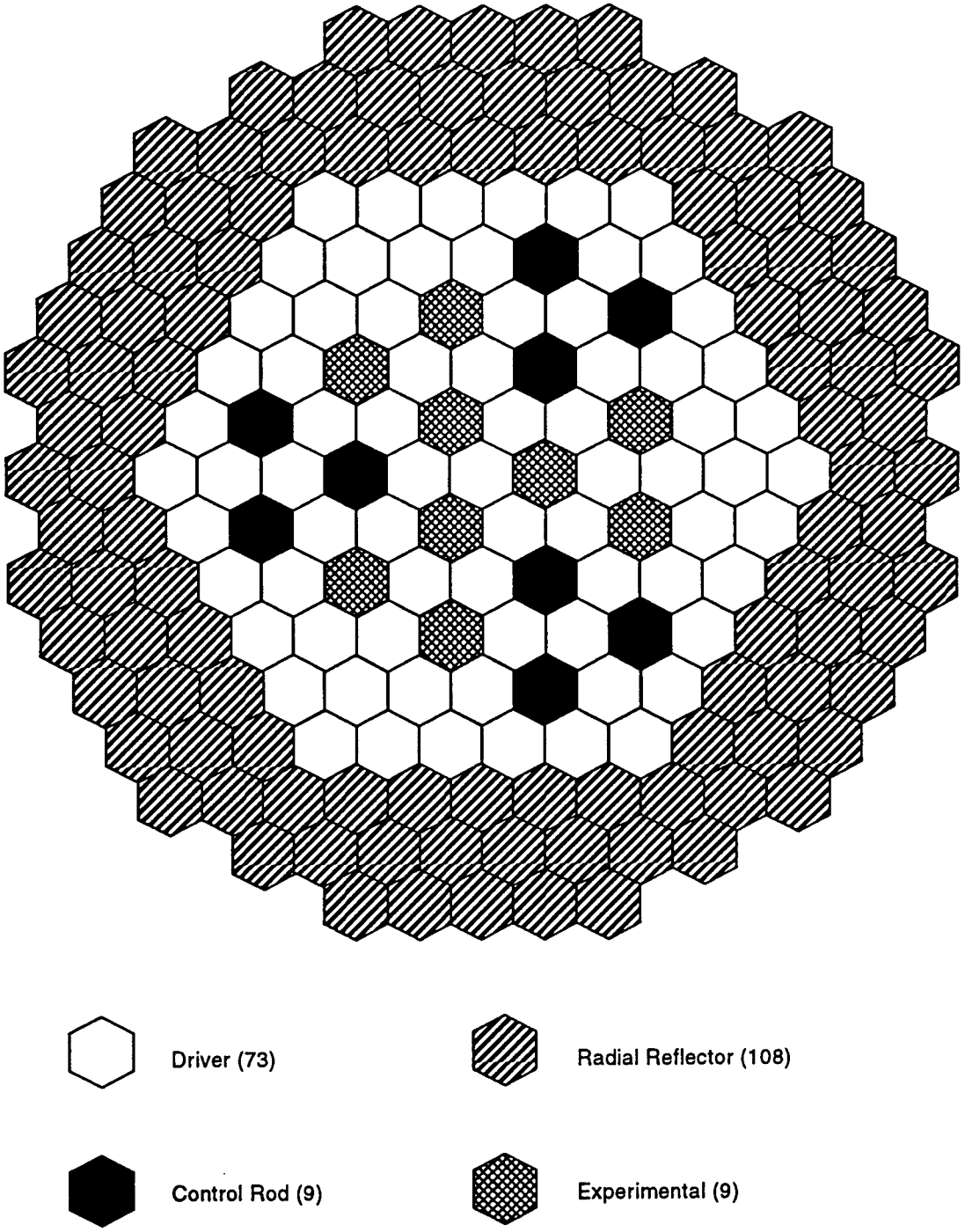

Figure 2-1. FFTF core in a possible configuration for irradiation testing of materials. The positions positions and numbers of the fuel assemblies ("drivers"), reflector assemblies, control rods and instrumented test assemblies ("experimental") are as indicated (from [5]).

Table 2.1. Base (prior to shutdown) FFTF Driver Assembly Design

FFTF Driver	Base
Fuel Material	PuO_2-UO_2
Cladding and Duct Material	SS-316
Number of Pins per Assembly	217
Fuel Pin Diamter, in.	0.23
Cladding Thickness, in.	0.015
Pitch/Diameter Ratio	1.25
Fuel Smear Density, % T.D.	85.5
Active Length, in.	36
Duct Outside Flat-to-Flat, in.	4.57
Duct Wall Thickness, in.	0.120
Interassembly Gap, in.	0.155
Assembly Lattice Pitch, in.	4.725
Volume Fractions:	
Fuel (smeared)	0.35276
Gap	0.06455
Coolant	0.34632
Total Sodium	0.41087
Clad	0.11376
Spacer	0.02691
Duct	0.09570
Total Structure	0.23637

ex-core). The fuel pin bundle geometry for the driver assemblies is detailed in Table 2.1.

Each FFTF mixed oxide driver assembly contains 217 pins (0.23 in. outer diameter) with an active fuel height of three feet. The typical fuel management scheme consists of a 100–120 day operating cycle after which 1/3 of the fuel is replaced. The FFTF has demonstrated a capacity factor slightly over 75% over a 2 year period during which maximizing time under power was an operational goal.

The FFTF began operation in 1980 and continued to operate until April 1992. A shutdown order was issued in December 1993 by DOE as a result of a deemphasis of its advanced fuels and materials testing mission. The reactor

is now defueled and deactivation steps are in progress, with an estimated completion date some 6 years in the future. Restart for a T production mission may still be a reasonable option as only a small fraction of the major deactivation procedures have been carried out. In addition to reversing those steps, some equipment will require replacement or upgrading, and major reactor systems will require recertification for the 30–40 year total lifetime required for a T production mission.

The FFTF was designed for flexibility of operation, including the capability to carry out extensive manipulation of fuel and test assemblies efficaciously. This capability would also need to be exercised in a T-production mission. It is also noteworthy that FFTF successfully carried out many experimental tests to confirm that analyses of fuel assembly response to a variety of transients were correct. These tests made use of the in-core instrumented experimental assemblies shown in Figure 2-1.

The standard operating fuel of FFTF was a mixture of PuO_2 and UO_2, the Pu being mostly the fissile isotope ^{239}Pu. The U was "depleted", i.e., almost entirely ^{238}U ($\leq$ 0.2% ^{235}U). The maximum Pu fraction in the fuel was 25–30%. The ^{239}Pu generates nearly all of the neutrons needed both to sustain the fission chain reaction and to breed T by reacting with ^{6}Li. In a fast neutron spectrum, any ^{241}Pu present in the fuel (a tiny fraction in weapons grade Pu but about 10% in reactor grade Pu) acts about the same as ^{239}Pu, and ^{240}Pu (about 6% of weapons grade Pu and 30% of reactor grade Pu) acts almost as effectively. The ^{238}U also undergoes fission reactions with fast neutrons, but the fission cross section is substantially smaller than that of ^{239}Pu, and the capture-to-fission ratio for ^{238}U averages more than 1 in the FFTF spectrum.

2.3 Proposal to use FFTF for T Production

In light of the potential for FFTF to be an effective means of producing a substantial fraction of the T requirements for the U.S. nuclear weapons stockpile, ANL and WHC scientists have proposed to reactivate FFTF for this mission. The proponents believe that the reactor can be back in operation in 4 years producing T at a rate of about 1 kg/yr by the simple expedient of replacing existing reflector assemblies with ^{6}Li-containing target assemblies. The first target assemblies to be used would contain $LiAlO_2$. The target pins would be close to the design which has undergone extensive experimental testing for use in LWRs for T production.

The proponents propose to increase the T-production rate first to about 1.5 kg/yr and then to 2 kg/yr by 2005 by a sequence of modifications to the core configuration, the fuel enrichment and the target assembly material. To reach 1.5 kg/yr would require the use of ^{6}Li-containing targets ($LiAlO_2$) in-core in the 19 positions shown in Figure 2-3, and an increase in the Pu enrichment of the MOX fuel to about 40%. In effect, the neutrons absorbed by the ^{6}Li in-core must be compensated by removing ^{238}U absorbers and replacing them with a larger neutron source (more Pu). There is a substantial experience base for MOX fuel with up to 40% Pu-enrichment at EBR-II (Experimental Breeder Reactor-II at the Idaho National Engineering Laboratory) and up to 33% at FFTF (see [4], p.51). The proponents argue that the rigorous testing of in-core target assemblies and 40%-enriched MOX fuel assemblies can be carried out in a period of about 1 year while FFTF is in its initial 1 kg/yr T-production mode.

Achievement of 2 kg/yr would require replacement of $^6LiAlO_2$ by $^6Li_2O$ in target assemblies (to increase the density of ^6Li in the targets), additional in-core target assemblies and a further increase in Pu enrichment of the MOX to about 50%. Two possible production core configurations used in detailed calculations are shown in Figures 2-2 and 2-3, the first by ANL scientists and the second by WHC scientists. Both calculations yielded about 2 kg/yr as the T production rate, assuming FFTF operation at full power and 75% capacity factor. There is substantial experience with Li_2O for T breeding as part of the fusion research program, but there is very little experience with 50%-enriched MOX fuel. It is proposed that testing of Li_2O target assemblies and 50% enriched MOX fuel assemblies would take place for about 1.5 years while the FFTF core operates in its 1.5 kg/yr mode, in order to gain confidence in the safe and reliable operation of these assemblies.

The alternative possibility for producing 2 kg/yr by switching to a Pu-U-10Zr metal fuel having 42% Pu/58% U (see for example [5], pp 51-55) is just as far from the experience base as 50%-enriched MOX since this metal fuel has been tested up to only 31% Pu/69% U. Therefore, for simplicity, we will not discuss this option further.

The fuel required for FFTF restart can come from the supply remaining at the time the shutdown order was received. This supply will last approximately 18 months, by which time a new fuel source will be required. Use of MOX available in Germany was suggested by proponents. We have chosen to ignore this option as it may not be available to the U.S. for T production, and because doing so only postpones the date by which the U.S. must develop its own source. Proponents argue for developing this capability in a building at the FFTF site which was to be the Fuels and Materials Examination Facility

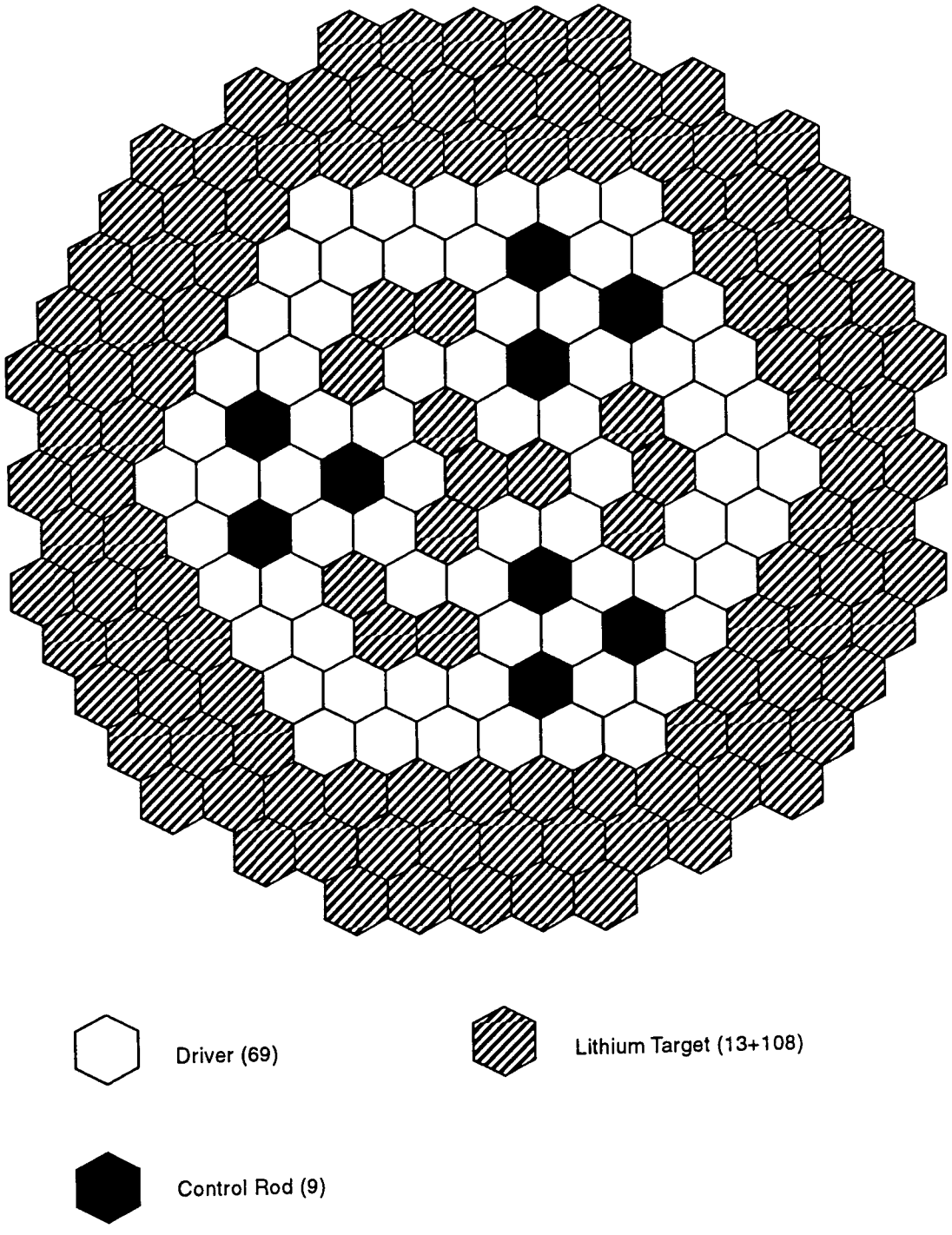

Figure 2-2. FFTF core configuration for producing 2 kg/yr of T as proposed by ANL (from [5]).

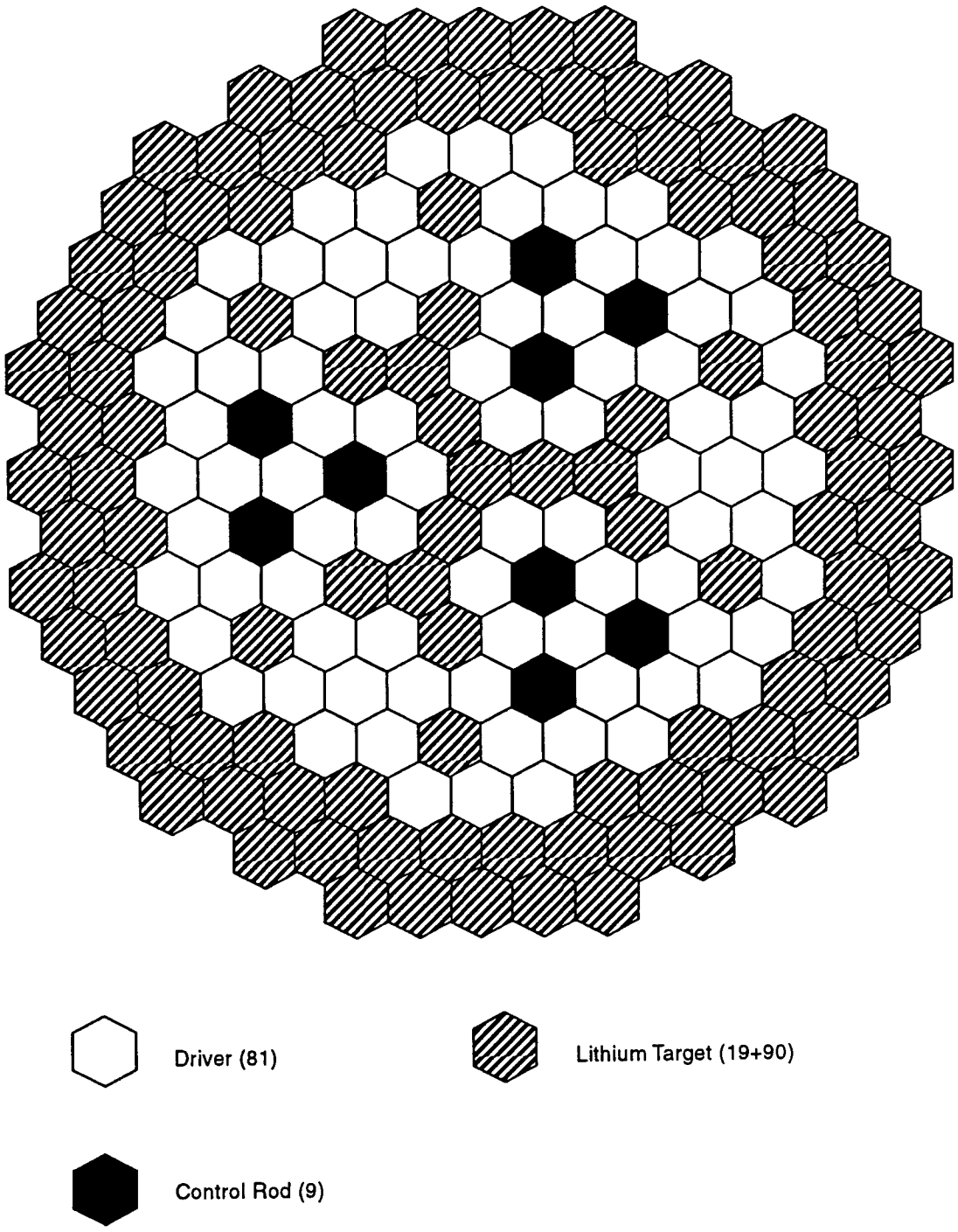

Figure 2-3. FFTF core configuration for producing 2 kg/yr of T as proposed by WHC (from [5]).

(FMEF) but which was never used for any purpose.

Before FFTF can be restarted and operated (modified as necessary) for a T-production mission, certain regulatory requirements will have to be satisfied. These include safety analyses and an environmental impact statement. In addition, it will be necessary to renegotiate the "Triparty Agreement" among DOE, EPA and the state of Washington concerning the deactivation of FFTF. Similar activities will be required before starting up FMEF as the fuel preparation facility.

2.4 A Simple Calculation of the 2 kg/year Limit

The nature of the FFTF core when fueled for a high rate of T production can be used to estimate accurately the maximum production rate given 400 MW_t (full power) operation and a 75% capacity factor. The average energy release per fission in a MOX-fueled fast reactor core heavily loaded with ^{6}Li for T production is very close to 210 MeV, or 3.36×10^{-11} J. This includes the energy released when neutrons are absorbed in ^{6}Li and in non-fission absorptions by Pu and U nuclei. Therefore, we calculate that 2.9×10^{26} fissions will occur in the FFTF in a year of full power operation with a 75% capacity factor. The fast neutron spectrum leads to an average number of neutrons released per fission of a Pu nucleus of about 2.9. For ^{238}U, it is about 2.5, but most neutron absorptions in ^{238}U result in γ-ray emission and no neutrons[2] instead of fission. For each fission one of the emerging neutrons must produce another fission in the next generation in order to sustain the chain reaction,

[2]The fuel of choice for a T mission is ^{239}Pu rather than ^{235}U because of a smaller number of neutrons emitted per fission (e.g. 2.5 for ^{235}U and 3.0 for ^{239} Pu at a neutron energy of 1 MeV) and fewer non-fission absorptions by ^{239}Pu than by ^{235}U.

leaving *at most* 1.9 neutrons (if all fissions involved Pu) available to do other things, including T production. Detailed calculations performed on possible FFTF core configurations by both ANL and WHC scientists indicate that at most 1.4 of these 1.9 neutrons will be absorbed by ^{6}Li and generate T. The remainder will be absorbed in structural material, in ^{238}U without inducing a fission or in the reactor coolant and control rods, or will leak out of the core. Therefore, the maximum production per year of T atoms by FFTF is 1.4 times the number of fissions, i.e., 4×10^{26} atoms of T. Since there are 2×10^{23} atoms of T per gram we obtain 2 kg/yr as the *maximum* T *production* rate for FFTF.

It is reasonable to ask to what extent the 2 kg/yr maximum we just obtained is an "absolute" maximum for FFTF. We understand that limitations in the dump heat exchangers truly limit the safe operating power to 400 MW. A major modification to the heat exchanger system (and perhaps the pumps, etc.) would be required to increase its capacity significantly if one wanted to increase the reactor power in order to increase T production. Another possibility is to increase the capacity factor of FFTF beyond its 75% rated value. We doubt that a significantly higher capacity factor can be achieved and sustained because the 75% level was exceeded by a few percent only in the two years during which maximum operational time was a goal. The problem is that there is a minimum down-time that is determined primarily by the need to refuel. Were we to postulate that the capacity factor could be pushed up to an average of perhaps 80%, the maximum T production per year would increase by only 6.7% to approximately 2.1 kg.

The only way to substantially increase T production without substantially increasing the power would be to use more of the 1.9 neutrons per ^{239}Pu

fission than the 1.4 we postulated above as being the maximum. Most of the unproductive 0.5 neutrons per fission are absorbed in ^{238}U or in a control rod, or are lost from the top and bottom of the core. Elimination of most or all of the ^{238}U in the fuel assemblies, substitution of ^{6}Li for boron in control rods and the use of ^{6}Li-containing material in place of upper and lower reflectors in the fuel assemblies are all possible, in principle. However, there is no operating experience in FFTF, EBR II, or anywhere else to our knowledge, on the basis of which we could be confident that any of these changes could be made without compromising the safe operation and mechanical integrity of FFTF. In fact, in Reference [7], WHC scientists have made the following statement [8] concerning T production beyond 2 kg/yr:

> "Incremental production increases above 2 kg/yr can be accomplished by adding lower axial targets in fuel assemblies and adding target rods in place of the boron in Row 5 control rods. A rate of 2.2 kg/yr is possible but assessment of the confidence level for production above 2 kg/yr would require a mechanical design effort that is beyond the scope of the current effort."

We conclude, therefore, that for all practical purposes 2 kg/yr should be considered to be within 10% of the absolute maximum T production rate that can be achieved and sustained using FFTF.

3 TECHNICAL ISSUES

3.1 System Lifetime

The 10-year long operating record of the FFTF, together with its design features plus experience with long term operations of other reactors with high fast neutron fluxes (e.g. EBR-II) give a basis for confidence in extending the lifetime of FTTF for producing T to some 20–30 years after restart under the anticipated operating conditions.

Originally a 20-year lifetime was established for FFTF, with some components slated for replacement after 10 years, because of the possibility of accelerated aging effects, such as creep, fatigue, and loss of ductility due to fast neutron irradiation and elevated temperatures ($\sim$ 450°C). Extensive data gathered during its operations revealed that the FFTF experienced less significant material damage than originally assumed, in part due to fewer operational transients than estimated. Together with detailed analyses supported by both experience and analyses of long-term EBR-II operations, these data have led DOE to approve a lifetime extension to 30 years for a number of plant components.[3] Other lifetime extension analyses for some of the remaining components have been undertaken but not yet completed. These analyses would not be required prior to a restart of FFTF because the initial certification period has at least 3 years of full-power operation to go for all components.

[3]In this connection we note that the T production mission may contribute to life extension because some neutrons that would have diffused through the Inconel reflector will be absorbed by the ex-core ^{6}Li target assemblies, thereby avoiding a fraction of the neutron damage to structure around the core.

An area of particular concern for reactor life extension is the inner radial shield that might experience a lock-up with the core restraint module static ring assembly due to irradiation-induced creep and swelling. This part of the reactor cannot be replaced, but an analysis that still awaits DOE approval supports a 29-year life extension (with a 2σ safety margin).

It is reasonable to accept the conclusion of the DOE Office of Nuclear Energy, WHC, and ANL, on the basis of what has been learned from already-completed extensive analyses, the FFTF design, and established operating conditions for tritium production at the 2-kg/yr goal, that it will be possible to operate FFTF reliably for 20–30 years after restart.

3.2 ^{6}Li–Containing Targets

Compounds that contain ^{6}Li will form T via the (n, T) reaction. Since T will permeate through conventional cladding materials, it must be contained within target assemblies by permeation barriers, gettering, or both. There is an extensive knowledge base on how to do this, and do it well, from experience in both thermal and fast reactors.

The two solid ceramic targets of interest for producing T with the FFTF contain ^{6}Li either as lithium aluminate ($LiAlO_2$) or lithium oxide (Li_2O). Their relevant properties for this application are summarized in Table 3.1 taken from Reference [5]. The experience base for $LiAlO_2$ is in the test program for T-producing targets for use in an LWR. The modifications of those targets needed to utilize $LiAlO_2$ in FFTF assemblies would be minor. For Li_2O, there is test experience in the fusion research program. Japanese test

Table 3.1

Properties of Lithium Compounds				
	Melting Point °C	Th. Cond. w/m°C	Density gm/cc	Li Density gm/cc
Li_2O	1700	5.7	2.01	0.93
$LiAlO_2$	1600	2.9	2.60	0.27

data is especially relevant and suggests that practical levels of T production can be achieved at the temperatures present in FFTF long before material integrity might become a problem.

The technology for fabricating such targets and recovering tritium from them is well established. Care is required in maintaining a high performance of the permeation barrier (to prevent loss of T) at the elevated operating temperatures of the FFTF. We believe that this presents no serious risk. In order to assure safe and reliable operation, however, a lengthy and rigorous in-reactor testing program will be required.

3.3 Mixed Oxide Fuel

The level of Pu enrichment of the MOX fuel to be used for T production at FFTF, and the rate at which the fuel will be used, depend on the rate of T production. At a 2 kg/yr rate, close to one ton of PuO_2 is required per year. Presently available MOX fuel for FFTF can support the proposed initial 1 kg/yr T production rate for nearly 1.5 years. Further operation at this or any higher level will require fabrication of new fuel assemblies. This would be accomplished at the Fuel and Materials Examination Facility (FMEF) at Hanford, a building colocated with the FFTF, which has plenty of space for

all necessary operations. Los Alamos has some capability to make the needed fuel assemblies, but only in small quantities, perhaps 6 assemblies per year. This is far from enough; T production at 2 kg/yr requires some 50 assemblies per year.[4]

There now exist 56 unused FFTF fuel assemblies, 2 assemblies-worth of MOX pins, and 120 partially-irradiated assemblies. They all contain 25-30% Pu, an enrichment which can be used for a T production rate up to about 1 kg/yr only. These available assemblies would be adequate for FFTF operation over the time required to prepare FMEF for MOX fuel production.

FMEF was built as a fuel fabrication facility as well as for handling other materials. It is the logical choice for fuel fabrication for FFTF on the basis of location, capacity and safety. The design of the fuel fabrication line must take into consideration potential safety issues posed by the higher Pu-enrichment that will be required for higher production rates of T. (Safety consideration will be taken up more fully in the next subsection.)

The Pu stock to be used for the fuel assemblies made at FMEF largely comes from declared-surplus pits stored at the Pantex plant, where excess nuclear weapons are dismantled. Some 21 tons of weapons-grade Pu metal stored at Pantex would be available. Up to 12 additional tons of Pu are available from Rocky Flats, half in metal form [9]. In the various cost analyses of FMEF/FFTF, it is assumed that the Pu itself is free, the great expense in producing it being viewed as a sunk cost. However Pu from the pits cannot be immediately used in the fuel assemblies; the pits must

[4] As noted in Section 2.3, we have chosen to discount the potential availability of MOX fuel from Germany both because there is no certainty that it would be made available to the FFTF and because its use would only delay the need to develop a long term Pu-enriched MOX source in the U.S.

be dismantled and processed to reduce americium content to no more than 1,000 ppm and to remove the gallium. The americium reduction is needed for safe handling of unirradiated fuel assemblies, and the gallium removal is because of potential incompatibility with Zr cladding on fuel pins. The required processing of the Pu would also take place in the FMEF.

The amount of Pu stock available, given the need for close to one ton PuO_2 per year, will support about a 30-year production run for T at FFTF. Further production would require further encroachments on weapons-grade Pu (available perhaps from further reductions in the U.S. arsenal under START provisions), or alternative methods of making the tritium.

The fuel assemblies require levels of Pu enrichment that depend on the desired T yield. The enrichment must increase from 30% at 1 kg/yr to about 50% for a rate of 2 kg/yr. There is no FFTF experience with such a high enrichment. However, since EBR-II tests [10] of 40%-enriched MOX showed little difference in steady state irradiation behavior between it and 30% MOX, there is reason to believe that 50%-enriched MOX will also be a satisfactory fuel in FFTF. This, of course, must be tested, as has already been discussed.

3.4 Safety and Environmental Issues

Restart of FFTF for producing tritium will require a revision of its original Safety Analysis Report (SAR), adapted and upgraded to the proposed altered operating conditions, especially for a 2 kg/yr production goal, as well as to updated safety standards. A Probabilistic Risk Assessment (PRA) that had been initiated and was in progress before shut-down will also have to be

completed in order to meet all DOE requirements (and the intent of NRC regulatory requirements as well). Environmental issues in accord with the National Environmental Policy Act will also have to be resolved. With regard to regulatory reviews in preparation for restart, it should help that the FFTF has had an excellent safety record and met all issues raised by NRC staff prior to start of operations in 1980.

Among the most important early activities that must be undertaken prior to regulatory review and restart are analyses to establish the safety of the facility in the event of "worst case accidents". For example, concerns have been raised about the effect on safety of the high fuel enrichment for 2 kg/yr operations and the associated reduction in number of driver assemblies, together with the requirement of changing an increased number of target assemblies per cycle. Adding plutonium oxide to uranium oxide lowers the melting point and thermal conductivity of the mixture, leading to more stringent requirements on power production per unit length of assembly than in the baseline FFTF operation.

Aside from the requirement of high enrichment, a T production rate of 2 kg/yr necessitates that fuel assemblies in the core be replaced by Li target assemblies. Not only does the Li replace ^{238}U and displace Pu, it acts as a strong neutron poison. Furthermore, it changes the Doppler coefficient (a component of the change of reactivity with temperature) by absorbing slow neutrons that would have been absorbed by ^{238}U. As a result, the operation of the reactor needs to be carefully analyzed, and experiments will have to be done to confirm and validate the analyses during 1–1.5 kg/yr operational modes. Although there are no identified critical issues or technical "show-stoppers", there is a lot of work still to be done to complete necessary con-

firmatory analyses.

Another issue related to safety is the impact of feeding excess weapons-grade (WG) Pu to the FFTF on the eventual safe and secure disposal of that material. Under the operating conditions for maximum production of T, close to one ton per year of fresh fuel containing 50% WG Pu (94% ^{239}Pu) would be loaded into the FFTF. After a cycle of about 100 effective full power days, a portion of the fuel would be removed from the core still containing about 40% Pu. This would still be WG Pu because the energetic neutron spectrum in the reactor induces fissions in Pu^{240} together with Pu^{239}.

In fact, the ratio of Pu^{239} to fission products in the "spent" fuel from FFTF would be considerably larger than that from a normal production reactor, and also much larger than that from an LWR. In addition, the spent fuel would be so reactive that it would have to be protected against fast criticality much more conservatively than other spent fuel during cool-down and long-term storage. Because of the high Pu content, the spent fuel will eventually have to be reprocessed (either by dilution with ^{238} U by a factor of 10 or by removing the Pu) to prepare it for disposal.

The options would be to dilute the material with a much larger amount of depleted uranium, so as to reach a Pu/U ratio something like spent LWR fuel, or to separate the Pu and to burn it again in LWRs so that the second-generation spent fuel could be disposed of directly, e.g. in Yucca Mountain. In other words, feeding excess WG Pu to the FFTF will not assist with the disposal problem of excess WG Pu.

4 PRODUCTION LEVELS AND ASSOCIATED RISKS

4.1 1 kg/yr

The initial core configuration at restart to produce 1 kg/yr of T would retain, unchanged, the standard in-core fuel assemblies, and replace the 108 Inconel reflectors in the ex-core by lithium aluminate ($LiAlO_2$) target assemblies. The $LiAlO_2$ targets are similar in design (and somewhat simpler) to those developed for the light water reactor program. Their technology is judged to be reasonably well established, and their operation for four 100-reactor-day long cycles well within tolerances. We agree with all parties that this goal can be achieved with high confidence, assuming (as for the higher production levels) that FFTF operates at 400 MW_t and with a 75% capacity factor.

4.2 1.5 kg/yr

To achieve a production yield of 1.5 kg/yr will require a number of changes and developments that lie outside the current FFTF experience base. These include enriching the reactor fuel to about 40% Pu (for which there is EBR-II experience) and demonstrating that $LiAlO_2$ target assemblies can operate in-core in the 19 locations illustrated in Figure 2-3. Initial confirmatory operating experience for these developments would have to be acquired

be acquired with the FFTF in its 1 kg/yr T production mode. Factors that need to be understood include changes in power distribution in the core, the effect on the $LiAlO_2$ targets of the high energy neutron flux in FFTF relative to the thermal spectrum in LWRs for which the $LiAlO_2$ targets have been developed, and the slightly lower melting temperatures of the fuel when operating with enriched fuel pins. These required developments are not expected to be technically very challenging but will take serious study. We agree that one can have confidence in the FFTF achieving an annual 1.5 kg production goal but caution that the bureaucratic/regulatory requirements may be time consuming (e.g., need to certify the reactor for safe operation with the enriched fuel).

4.3 2 kg/yr

This level of production will require two significant changes in FFTF fuel and target loadings. Target assemblies loaded with $LiAlO_2$ will have to be replaced, both in- and ex-core, by Li_2O-loaded ones.[5] In addition the Pu fuel fraction in the driver assemblies will have to be increased to about 50% weight fraction.

There already exists an extensive data base, fabrication experience, and T recovery technology for both ceramics, $LiAlO_2$ and Li_2O. This provides some confidence that no great risks will be encountered in using Li_2O target assemblies in FFTF. However, as noted earlier [Section 1.2, Point 4] careful testing will be required to confirm, not only safe and reliable operations

[5]The analysis by the Tritium Office of DOE's Defense Programs [2] assumes that the higher ^6Li atom density (by a factor of 3.4 in Li_2O relative to $LiAlO_2$) will also be required in in-core targets in order to achieve a realistic 1.5 kg/yr yield rate.

under the anticipated FFTF operating conditions, but also to establish the high level of retention and recovery that are required to achieve a steady production rate at the maximum 2 kg/yr level.

There are concerns about extending the fraction of Pu in the MOX fuel to 50%, by weight, because this lies outside FFTF experience. The actual detailed operating parameters would depend on the fuel configuration adopted. We have already noted that experience with MOX fuel pins with Pu enrichment up to 40% suggests that there are no factors that will preclude steady operations at 50% enrichment. However lack of direct irradiation experience, together with the potential of a reduced margin to fuel melting temperatures and possibly the necessity to reduce the initial operating power during the first few days after loading fresh fuel to avoid some fuel melting at peak power locations, means that a serious measurement program will be required before confidence can be placed in achieving the full 2 kg/yr as a safe and reliable T production rate.

Overall, we find a T-production rate of 2 kg/yr to be a credible goal for FFTF because 1) it appears to us that there are no technical "show stoppers" so long as necessary development and test programs have adequate resources and time; 2) 2 kg/yr is not ruled out by the basic considerations discussed in Section 2.4; and 3) two independent detailed core design calculations with different but potentially realistic core configurations carried out by WHC and ANL scientists gave results within a few percent of this rate. However, in our view, everything will have to work up to full potential without a hitch to actually achieve a 2 kg/yr T production rate on the proposed schedule.

5 SCHEDULING ISSUES

Our principal concern with the restart of FFTF for the purpose of producing T is that there is the possibility of lengthy delays in the regulatory and permitting processes. In this section we first briefly describe the major steps in these processes. We then list a few of the concerns that are likely to be raised as part of the regulatory and permitting processes. Convincing regulators and the general public that all possible "worst conceivable accident" scenarios for the 2 kg/yr production reactor configuration have been analyzed, and that no such accident would jeopardize the public or the environment, will probably take more time and effort than doing the analyses themselves. We also consider how outstanding technical issues might be impacted if regulatory delays do occur. Finally, we comment on the lag between production of T and its delivery to the stockpile. We consider the latter a far less important concern than the first two because that lag time is predictable while regulatory delays, and even delays related to development and testing, are not.

5.1 Bureaucratic Barriers

FFTF restart must be preceded by meeting a collection of regulatory requirements, obtaining necessary policy decisions and renegotiating the part of the Tri-Party Agreement among DOE, EPA and the state of Washington that covers the FFTF deactivation. Most urgent among these is probably the necessity for DOE to make a policy decision regarding its plans for T-

production. In the Record of Decision (ROD) in the Federal Register of December 12, 1995, DOE states its intention to pursue two alternatives for 3 years:

1. make preparations to purchase a commercial light water reactor (CLWR), or irradiation services in a CLWR with an option to purchase the reactor; and
2. design, build and test critical components of a particle accelerator-based system.

DOE will select one of these alternatives as the primary option and the other as a back-up within three years. (Other issues covered by the ROD in question pertain to T extraction and recycling at Savannah River, which would also be the site of the accelerator if one is built.) Clearly, the December 12, 1995 ROD will have to be amended, or a new one issued, including FFTF in DOE's T-production plans. However, prior to this being possible, environmental requirements of the National Environmental Policy Act (NEPA) must be met. Furthermore, the deactivation order for FFTF issued by DOE in December 1993 must be reversed. If DOE chooses to go forward with a T-production mission for FFTF as proposed, the Department must also release excess WG Pu for T-production and must be willing to deal with Pu-enriched spent fuel after its use in FFTF (see Section 3.4).

The major regulatory action having to do with environmental requirements is preparation of an Environmental Impact Statement (EIS) covering both restart of FFTF and opening the FMEF as a fuel preparation facility. In addition, permits will be required in accordance with several laws and regulations of both the Federal government and the state of Washington, including

the Clean Air Act, the Clean Water Act, the National Environmental Policy Act, the State Environmental Policy Act, the State Waste Discharge Permit Program as well as several others. These may not be as time-consuming as preparation of the EIS, but if they involve additional public hearings, they could take a longer time than expected in total.

The DOE agreed to make the FFTF subject to the Triparty Agreement, which is largely concerned with environmental cleanup at Hanford, because it is currently shut down and being decommissioned. Under the Triparty Agreement, there are enforcible milestones in the deactivation process. DOE must renegotiate that agreement and obtain EPA and state of Washington agreement to eliminate the deactivation milestones and change the mission of FFTF to T production.

Obtaining approval for restart from the Defense Nuclear Facilities Safety Board (DNFSB) requires completion of up-to-date Safety Analysis Reports, a Probablistic Risk Assessment and other associated safety reports; the conduct of an Operational Readiness Review (ORR); and preparation of any other documentation the DNFSB might request (such as additional data on target assembly performance in a reactor under conditions more relevant to FFTF, i.e., from EBR-II). The Board then performs its review and can (and probably will, based upon experience in the recent past) hold public hearings. It is our impression that FFTF facility documentation has been thorough and complete and is up to date, thereby making preparation of documents for the ORR relatively simple. However, we are concerned that safety issues related to the T production mission, such as those discussed in the next subsection, will cause the regulatory process to drag on as more and more postulated "worst case accident" scenarios have to be analyzed.

With all of these activities to be accomplished in a relatively short time (T production is proposed to start at the 1 kg/yr rate in only 4 years), it seems clear to us that there will have to be a concerted effort by many organizations to minimize the total time required to complete the regulatory process. Therefore, if the DOE decides to go ahead with a T production mission for FFTF, the Department will have to call upon resources from Hanford, from ANL and other DOE laboratories, and from DOE headquarters on a high priority basis to complete the environmental, safety and technical analyses, and all the associated regulatory processes that must precede the restart, in a timely manner.

5.2 Perceived Safety

A major concern of the T producing FFTF is not that it is unsafe but that it is vulnerable to public opposition and regulatory delay. To be technically safe is not enough. It has to be perceived as safe by often unsympathetic regulators and by nervous citizens. This makes it truly difficult to predict a start-up schedule with any confidence since the technical factors are not the only relevant ones. They may not even be the determining ones.

The following features of the reactor are likely to raise doubts in the minds of the public, and must be clearly covered by safety analyses:

1. The reactor contains 1400 kilograms of weapons-grade plutonium in a compact configuration close to prompt criticality. Detailed analysis is required to make sure that no accident scenario, no matter how unlikely, can lead to prompt criticality and an explosion. U.S. reactors have not

experienced a Chernobyl-type explosion because of their safer designs. We must assure that if FFTF is reactivated for a T-production mission, it meets the same safety standards as other operating U.S. reactors with regard to the possibility of explosion.

2. Safety analyses involving the 50% enriched MOX, for which there is no experience base, must be extremely thorough.

3. With the planned reactor power and the planned 50% plutonium fraction, the peak temperature in the fuel elements will be close to the melting-point at full power, especially during the first few days after fresh fuel is loaded. Because of uncertainties in heat-transport from fuel to coolant, the peak temperature cannot be predicted accurately. It must be measured in operational tests. The reactor may have to be operated below full power for the first few days after a fuel loading to be sure to avoid centerline melt. If so, this must be clearly spelled out in operating procedures.

4. In the Final Safety Analysis Report on the FFTF, published in 1975 (before the FFTF began to operate), two kinds of hypothetical severe accidents were analyzed. The Transient Overpower Accident assumes a large fluctuation in reactor power, which ceases to rise only when a substantial fraction of the fuel melts and is swept out of the core by the flow of coolant. The Loss of Coolant Flow accident assumes that the fuel melts in place and then slumps to a more compact configuration. Detailed analysis showed that even these severe hypothetical accidents would be contained inside the containment shell of the reactor. However the fact that they might even be possible will raise concerns in this post Three-Mile-Island and Chernobyl world, especially with FFTF using 50%-enriched MOX.

5. When the FFTF is converted to T production by putting ^{6}Li target assemblies into the core, a new possible accident has to be considered. This is a Loss of Coolant Accident involving one or more of the Li assemblies. The lithium could melt and be swept out of the core, resulting in a rapid rise of reactivity and possible prompt criticality.

While these severe accident scenarios may be far-fetched, the burden of proof rests with DOE and its contractors to convince the public that they will not happen. Lengthy procedures, probably including public hearings, will be required before the FFTF can be restarted and licensed for operation with new fuel-elements. Under these circumstances, no fixed time-table for T production by FFTF can be assured.

5.3 Development and Testing

In previous sections we have discussed the need to carry out a development and testing program on ^{6}Li-containing target assemblies and MOX fuel having Pu-enrichment above 30%. As we are not familiar with all of the relevant regulations we do not know what, if any, development and test steps can be carried out before, for example, a new or revised ROD is issued concerning a T-production mission for FFTF. Since the ROD must await the completion of the EIS, any delays in the completion of the EIS and then in issuing the ROD will impact the schedule of those portions of the development and testing program which require the new or revised ROD. Similarly, the restart of FFTF requires regulatory review and approval, the initiation of which depends upon several previous steps being completed. Since the ramp-up in T production rate from 1 kg/yr to the FFTF goal of 2 kg/yr

requires a few year testing program using FFTF, every significant delay in the restart schedule for FFTF will delay the achievement of the 2 kg/yr rate by about the same amount of time.

We have been assured by proponents that the T-production schedule was drawn out as long as it is to include time for such delays, as well as possible delays in the development and testing program itself. However, we remain concerned that even a dedicated effort to foresee all possible delays in starting or restarting any nuclear reactor for any purpose in the U.S. in 1996, and especially for special nuclear materials production, is likely to be unsuccessful.

5.4 The Lag Between Production and Delivery

It is obvious that production of the first gram of T in FFTF after restart is not the same as the delivery of that gram to the weapons stockpile. The T must build up in the assemblies to a high enough level to make their removal and processing worth while. With FFTF restart in 2001, 2 kg of T would not be actually available to the stockpile until 2004 (see for example Reference [2], Fig. 5-1). While this is certainly correct, those 2 kg put off the year by which a steady rate of new T-production is needed. Also, once in-core target assemblies can be used, the time lag will decrease because the rate of T-production in-core will be higher. Furthermore, it will be worthwhile to determine an optimum practical schedule for moving ex-core target assemblies in-core for the purpose of minimizing the T lost to decay (5.5% per year) before assemblies are processed for T removal.

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