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THE FEASIBILITY OF LITHIUM
ADDITION AS AN
ALTERNATE SHUTDOWN METHOD
FOR THE FAST TEST REACTOR

FEBRUARY 1971

HANFORD ENGINEERING DEVELOPMENT LABORATORY
UNITED STATES ATOMIC ENERGY COMMISSION

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THE FEASIBILITY OF LITHIUM ADDITION AS AN
ALTERNATE SHUTDOWN METHOD FOR THE FTR

INTRODUCTION

The Fast Test Reactor will be provided with two independent⁽¹⁾ shutdown systems. These systems are being designed to preclude "common-mode" failures that could prevent safe shutdown of the reactor. As presently designed, both the primary and secondary shutdown rods must pass through instrument-tree guide tubes to reach the active zone of the core. However, instrument tree displacement has been identified* as a potential common-mode failure which possibly could cause restriction of rod entry into the core.

Because of the importance of the diversity and independence of separate shutdown systems, re-assessment of alternate shutdown methods for the FTR has been undertaken by ARD.^(2,3) While that study, by HEDL/ARD agreement, is limited to mechanical methods, this study complements the ARD study by the additional consideration of five different methods of shutdown. Four of these methods utilize liquid poison, and the other utilizes a primary and secondary system of boron carbide and tantalum poison rods, respectively.

SCOPE

A soluble liquid metal poison system in conjunction with a mechanical system has the advantage of providing diversification and would thus preclude common-mode faults associated with two mechanical shutdown systems which are similar. The potential use of lithium as a neutron absorber

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* See Appendix A.

for FTR shutdown* was suggested by J. Herb⁽⁴⁾ early in 1968. Other investigators⁽⁵⁻⁸⁾ since have explored the large variety of available possibilities and have concluded that molten lithium is the only logical choice of liquid poison for use in a sodium system. This choice was accepted after a review of these and other prior investigations. Accordingly, the scope of this report is limited to an examination of lithium as a potential liquid poison for usage in alternate shutdown systems for the FTR.

The advantages of lithium are: high neutron absorption cross-section, miscibility with sodium, low melting point ($\sim 180^{\circ}\text{C}$) and high boiling point (1317°C), and high specific heat. Four shutdown methods utilizing lithium were considered: addition of lithium to the primary coolant, a closed loop, and an empty thimble; and a lithium-antimony fuse. The relative worth of the first three of these methods can be found in Table B-2. Reactivity transients were not calculated.

METHODOLOGY

Method No. 1, Lithiation of the Primary Coolant

A relatively low concentration (< 0.6 w/o) of ^6Li in the FTR core coolant would produce a negative reactivity worth of approximately $2.5\% \Delta k/k$ (Appendix B, Table B-2). The mutual solubility of Li and Na at this low concentration and with temperatures above 98°C (Figure 1) enhances the possibility of using ^6Li as an alternate shutdown method. However, gross amounts of lithium in storage would be required to rapidly produce and sustain this required coolant concentration.

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*By the reaction: $^6\text{Li} + n \rightarrow ^3\text{H} + \alpha$

FIGURE 1. Phase Diagram, Lithium-Sodium

A method that adds Li directly to the plenum immediately below the core support structure has been suggested.⁽⁶⁾ Suggested mechanisms for this method involve sodium valves and actuators operating under sodium in the in-reactor environment. While such mechanisms are probably feasible, they are removed from current technology and their use would involve lengthy and costly development. Therefore, to introduce lithium below the core, a large reservoir external to the reactor vessel would be required. Sufficient mixing with the sodium probably could be obtained by discharge from a sparge ring mounted under the core, and the Li-Na mixture would be washed upward through the core. If the lithium supply were immediately depleted, fresh unmixed sodium would enter the core and remove the poison. Consequently, a sufficiently large Li reservoir would be required to last until the entire primary was mixed to the correct shutdown concentration. If the primary inventory is taken to be 10^6 pounds, then about 6000 pounds of ^6Li would be needed to obtain a negative worth of $2.5\% \frac{\Delta k}{k}$. This amount of ^6Li is equivalent to 200 ft^3 (~ 1500 gallons) of storage-tank capacity. If the flow rate through the core is taken to be 3900 lb/sec , then the Li flow rate should be at least 30 lb/sec ($\sim 450 \text{ gpm}$) added over about 200 seconds. This time interval would allow almost ten primary loop transport cycles to produce good mixing. If the isotopic purity of the lithium were reduced, the storage and flow requirements would be increased correspondingly up to the overflow limit of the primary system. Since adequate storage space ($>200 \text{ ft}^3$) does not exist in the immediate vicinity of the reactor vessel, the lithium would have to be piped from some distance away. To preclude any unduly long transport time ($>3 \text{ sec}$), a valve would be

necessary at or in the reactor vessel. However, if this valve should leak, a gradual buildup of ^6Li would occur in the primary sodium during reactor operation, and operation with lithic coolant would worsen the severity of the reactivity increase associated with the postulated central voiding of the core. The formation of solid hydrides in the primary system is possible from the reaction of the tritium, produced by neutron absorption, with the sodium and lithium coolant mixture. A complex valving system interposed between the lithium and reactor coolant would reduce the reliability of the poison addition when needed. Storage tanks and piping of the lithium addition system would require the use of exotic materials (Appendix C) to reduce corrosive attack, and would require heaters and insulation for maintaining a temperature of about 400°F to assure liquidity of the poison.

By extrapolation of rough cost data obtained from a variety of sources (Reference 9 and Appendix C), it appears that ^6Li , as a metal of about 99 percent isotopic purity, would cost as high as \$3,000/lb. Perhaps, by special arrangements, a lower price could be negotiated for gross quantities at lower isotopic purity. In such a case, an optimistic estimate of the procurement cost of ^6Li appears to be about \$1,000/lb as metal of 95 percent purity. If so, the lithium inventory to poison the coolant system would cost about \$6,000,000.

Recirculation of the lithiated coolant would jeopardize⁽⁵⁾ the reactor internals (Appendix C) even with the reactor shutdown. Consequently, further action required after achieving subcriticality and stabilizing or unloading the core would be either separating the lithium from the sodium or

discarding the primary system inventory. The costs of either process would be in addition to those costs mentioned thus far, as discussed below.

Separation of Lithium from Sodium

When considering the problem of separating the two metals, it is instructive to consider the phase diagram of the two components (Figure 1). For example, if a Li-Na mixture of 90 w/o sodium is at, say, 400°C, the solution is completely homogeneous. In fact, so is any mixture above the system's critical solution temperature of 380°C. Lowering the temperature of a 90% Na solution will cause the formation of two liquid phases at about 250°C with the lithium-rich layer on top. The composition of each liquid phase corresponds to that at the intersections of the 250°C "tie-line" with each side of the "dome". Lowering the temperature further causes a change in the composition of each phase, corresponding to the dome intersections, until a 95.6 w/o sodium solution is reached in the sodium-rich phase. At this time, solid lithium forms, and the two liquid phases disappear if the temperature is lowered further. By so doing, one liquid phase remains which increases in sodium concentration as more solid lithium is formed until the eutectic is reached. Lowering the temperature further will freeze the entire system so that a mixture of solid lithium and solid sodium-lithium mixture at the eutectic composition is obtained. By contrast, if a Na-Li mixture richer than 99 w/o in Na and higher than 100°C is cooled, sodium freezes out until the eutectic is reached and the whole system then freezes at the eutectic composition.

From the foregoing considerations, it is obvious that separation of immiscible liquid layers, or freezing out of solids, has no use in the

separation of Na-Li solutions that are lean (<1 w/o) in lithium. For shut-down purposes, 0.6 w/o Li in the primary sodium is sufficient. Consequently, more exotic methods are necessary for lithium separation.

It has been suggested (Appendix C) that the lithium be removed by selectively hydriding the lithium at the appropriate temperatures followed by cold-trapping. The cold-trapping equipment alone is estimated to cost more than \$500,000, not including installation costs. As with storage, special alloys would be required to resist the corrosive attack of lithium. The size of such a system is impressive, some 8,000 to 10,000 gallons of crystallizer volume (Appendix C) would be required. The capacity is set by the ~6000 lb of Li that would be in the primary system. The size of the equipment is too large to be considered for inclusion within the containment system, and appropriate isolation valves and piping would be required for eventual connection to the primary piping system, if and when separation would be required. Significant safety hazards would be associated with operation of a lithium hydriding system. Separation would need to be carried to a high purity, otherwise the central sodium void coefficient of reactivity would be enhanced during reactor operation until lithium burnout was complete. Further, the development of an on-line lithium analyzer would be required.

Disposal of Sodium-Lithium Mixture

The alternative to separating the lithium from the sodium coolant, using an installed system for the approximate 1,000,000 pounds of active inventory, would be to dispose of the lithic batch. This would involve

"writing-off" some \$250,000 for sodium plus \$6,000,000 for lithium, and expending another \$250,000 for new sodium.

Presently, the most promising alkali metal disposition appears to be conversion to the hydroxide. The caustic concentrate would be used to neutralize acidic wastes from the 200 Area chemical separation processes. The tritium content poses no particular problem since only a few millieuries would be generated by shutting down the reactor from full power. However, the enormity of the disposal problem and the technical complexities of the methods and equipment with their associated costs, are outside the scope of this report. Some idea of the problems involved in removing the coolant after lithiation can be gained from the following schedule:

<u>Activity</u>	<u>Time (weeks)</u>
Cooldown of core	12
Fuel removal	6
Installation of drains	2
Drainage	1
Refill preparation	1
Fill	2
Reload core	6
Start-up tests	<u>2</u>
	32

The above schedule does not include clean-up of fuel elements or lead time for procurement of a new core loading if required. Also, about six 30,000 gallon tanks would be required, or twelve new tanks if a flush is

made, since excess tankage is not included in the project. Thirty-two weeks is equivalent to more than 5,000 hours. If the cost of unavailability is \$3,000/hr, then more than \$15,000,000 would be lost in time to restore the FTR to service.

Critique of Primary Coolant Lithiation

From the foregoing, it is obvious that Method No. 1 would require a multi-million dollar expenditure. Uncertainties in the method are the speed of addition of lithium to the core and the degree of mixing. These uncertainties are maximized at the lowest flow, this corresponding to natural convective cooling. Reduced primary system flow is normally programmed in event of an FTR scram so that the core dispersion rate would be an uncertain variable in either event. The principal uncertainty, however, lies in the inability to test the reliability of the end function without sacrificing reactor availability. The only apparent reason for considering this method of shutdown then, is for that singular, hypothetical reactor condition when all other shutdown systems have failed and time is not of the essence. Direct addition of lithium to the primary pump barrels in this case could be considered if a back-up emergency shutdown were deemed necessary. Transport time would be about ten seconds. However, before seriously speculating such drastic methodology, consideration of expanding the core by controlled restraint release; and, possibly, by withdrawal of a fuel assembly, might provide a more predictable effect.

The uncertainties of lithium additions to the primary system preclude assured protection from all serious accidents. It is concluded therefore, that the predictable cost of Method 1 is not justified because of the uncertainties of the potential benefits.

Comparison with LWR Practice⁽¹⁰⁾

There is a comparison of LMFBR's with LWR's that can be made regarding liquid poison additions as an emergency back-up to the regular shutdown systems. BWR's, for example, have a liquid poison system somewhat analogous to that suggested above for lithium addition to the FTR coolant. The BWR system, called the standby liquid control system, is capable of shutting down the reactor from full power to cold subcriticality even if withdrawn control rods cannot be inserted. A heated concentrate of sodium pentaborate solution is held in a storage tank external to the containment vessel. By manual operation of a switch in the control room, explosive-actuated valves are opened and one of two pumps operates. The solution, by means of suitable piping and penetrations, is added to the inlet plenum and borates the core coolant. Excess boron is available so that subcriticality will be maintained if additional cooling water is supplied by other auxiliary sources, e.g., when the vessel is separated from the condensers.

PWR's have a safety injection system similar in many respects to the system just described. Borated water, from the refueling water storage tank, is pumped on signal (coincidence of low pressure and low level in the pressurizer) through a quick-opening valve to a line teed into the reactor inlet piping. The primary purpose of injection is to limit fuel-rod cladding temperatures in the unlikely event of loss of reactor coolant.

A subtle but important difference between LMFBR's and LWR's should be noted regarding liquid poison addition. LWR's inherently have a strong negative void coefficient for partial as well as full voiding. If a PWR,

for example, is operating with borated coolant (chemical shim) and a central coolant void develops, the void coefficient is still safely negative. Adding pure water to an uncovered LWR core is equivalent to adding reactivity. Consequently, additional LWR coolant must be borated when added under those accident conditions wherein the worth of the available shutdown systems is inadequate to maintain subcriticality. By contrast, LMFBR's cannot tolerate an uncovered core immediately after shutdown (except, perhaps, for a fraction of a second) without excessive fuel damage. The FTR, for example, is designed so that the core cannot be uncovered. Therefore, the LMFBR soluble poison analog of an LWR is not applicable because of the basic difference in reactor emergency conditions.

Method No. 2, Addition of ^6Li to a Closed Loop System

As an alternative, the addition of ^6Li to a closed loop system avoids some of the problems associated with lithiating the primary coolant. The closed loop method has the following potential advantages over Method No. 1:

- . Faster core addition.
- . No corrosive attack on primary system nor vessel internals.
- . No increase in positive reactivity feedback from sodium voiding.
- . More than an order of magnitude reduction in amount of ^6Li required; hence, less cost associated with clean-up or disposal.
- . No hydride formation in primary system resulting from tritium-coolant reaction.

The disadvantages with Method No. 2 become apparent when the mechanical details of lithium addition to a closed loop are considered. A heated tank of lithium could be pressurized with argon and teed into the inlet branch-

arm piping of the in-reactor test section. On signal, the lithium could be released under sufficient pressure to backseat the sodium-supply check valve (Figure 2), and the test section would be filled with ${}^6\text{Li}$. The worth of such channel is about three percent ($\Delta k/k$), more than sufficient to shut down the reactor.*

A difficulty analogous to that encountered for core coolant addition arises, however, as it is necessary to continue ${}^6\text{Li}$ addition to prevent ${}^6\text{Li}$ washout by circulating sodium. The lithium coolant circulation would have to be continued after shutdown to prevent damage to the experiment unless the closed loop is limited to materials testing. Thus, external lithium storage requirements would be approximately 750 gallons, the active inventory in the primary system. This additional volume would be impossible to add to the existing closed loop design because the primary loop system runs full except for a small (2 to 12 ft³) ullage in the IHX which accommodates sodium density changes. Because forcing lithium into the closed loop would force sodium out to the cover gas system, temporary storage of the displaced sodium would become a complicated valving and piping problem. Further, space for a large volume of lithium would not be available in the immediate vicinity of the reactor. If lithium were to be added in the cell, about seven seconds at full-flow would be required for the slug to reach the test section. Stress limitations would prevent any appreciable improvements in this transport time.

A small lithium storage volume (<2 ft³) is potentially available in each one-third sector on the top face. Consequently, a possibility exists

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*See Appendix B.

FIGURE 2. Flow Diagram of Closed Loop System

of adding lithium to the annular interstices of three closed-loop, in-reactor assemblies. The improved heat transfer to the reactor coolant would thus preclude the necessity of continued loop circulation. Unfortunately, the problem of penetrating the loop spool piece with suitable piping has not proven tractable even in the conceptual stage.

To circumvent these related series of difficulties, it has been suggested* that a small, fully-charged lithium loop be placed in parallel across the in-reactor test section by teeing into the inlet and outlet branch-arm piping in the vicinity of the spool piece (Appendix D, Figure D-2). On signal, explosive-operated valves would move to admit lithium under pressure to the test section and block the inlet sodium flow. The timing of the effluent valve would be such that, when the slug of sodium initially in the core had been displaced into the downstream piping, the lithium flow would be diverted to the lithium loop. By such a system, it would be possible to deliver lithium to the top of the core elevation in about 1.2 seconds (Appendix D). The delivery time would be limited by the test pressure-drop and the storage pressure. The latter would be limited by the collapse strength of the pressure tube. The in-core amount of lithium would be dependent on the test configuration.

The parallel or "piggy-back" loop would not be without the aforementioned problems of corrosion, testability, and adverse effect on availability. Cost estimates must assign a worth to the test which would probably be a write-off, as would the in-reactor assembly. The cost of the lithium loop would be an additional item.

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* See Appendix D.

Method No. 3, Addition of ^6Li to an Open Thimble

As an alternative to Method No. 2, lithium could be added to a helium-filled thimble. This method essentially would retain the advantages associated with the closed loop lithium addition without the concomitant complexity and expense. More importantly, an improvement in entry time would be realized. Lithium could be added to a central-channel thimble in about one-half second (Appendix D), which would have a reactivity worth of about(-) four percent $\Delta k/k$ (Appendix B). The basic simplicity of the scheme is shown in Figure D-1 (Appendix D). The previously discussed difficulties of heating requirements, testing capability, corrosion, and expense of exotic alloys still are applicable. Attempting to circumvent these difficulties led to a consideration of introducing solid balls boronated with ^{10}B into the core, and the development of a conceptual sketch (not shown). The NPR, a dual-purpose, pressure-tube, thermal reactor, has a back-up shutdown system that utilizes small (~ 0.25 in) ceramic balls compounded with samarium oxide. This system has performed very nicely and effects shutdown by dropping the balls from hoppers into empty vertical channels on appropriate trip signal. The principal advantages of the ball-drop method are the attainment of end-function testability and comparative ease of recovery without a large loss in availability. A slight advantage exists in that the center-most channel could be used for the ball drop method. Ball recovery would be by means of a vacuum system. The principal disadvantage would be an increase in entry time by a factor of three, or about 1.5 seconds.

The worth of the boron ball-filled thimble surpasses that of the lithium-filled thimble as may be seen from Table D-2 (Appendix B). The worth of the empty thimble in the core is approximately $(-)$ 0.6 percent $\Delta k/k$. This decrease in reactivity would have to be compensated by increasing the enrichment of the remaining drivers. The end trade-off would be in the increase in linear heat generation rates and the decrease in Doppler coefficient with the attendant safety implications. These effects were not quantified because the scope of investigation lead beyond the study's charter.

If lithium had to be used for FTR shutdown, the addition of lithium to an empty thimble would be the logical choice of methods on the basis of speed, strength, testability, cost, reliability, and availability. The choice of channels for the lithium thimble is suggested as that now indicated for the oscillator (or closed loop), Figure 3. The closed loop opening in the head would be required to permit removal of the thimble liner, following a lithium injection, if the contemplated lithium removal method (reverse pressurization) does not function.

Method No. 4, Fusible Plug

To broaden the scope but to restrict the amount of liquid metal considerations, the writer has limited himself to submittal of one "blue-sky" concept. The basic conceptual arrangement, shown in Figure 4, consists of an elongated capsule that fits inside of a regular core duct. The bottom portion below the core is filled with ${}^6\text{Li}$. The lithium would remain molten because its melting point ($\sim 356^\circ\text{F}$) is below that of the core inlet temperature. The core section of the capsule would be filled with He at low pressure. Above the core would be a fusible metal plug held in place

NOTE: REACTOR CAPABILITY= 6 CLOSED LOOPS

FIGURE 3. Core Map November 1970

FIGURE 4. Fusible Plug Poison Addition

by pins to assure conduction into the solid and to support it while frozen. The fusible metal suggested at this time is pure antimony (m.p. $\sim 1166^{\circ}\text{F}$). With excessive outlet temperature in the region, the Sb fuse would melt. Sufficient volume of Sb would be present to fill the core section. In the melting process the lithium would rise into the vacant core section.

Analogous to the discussion for the Li-Na binary (at appropriate temperatures and concentrations), homogeneous solutions of lithium in antimony would be formed. The literature⁽¹⁵⁾ indicates the formation of several higher melting intermetallics (e.g., Li_3Sb) which could pose some problems. Clearly, such a fuse would necessitate a development program to investigate the binary phase systems, the allowable materials, the necessary melting rates, neutron absorption, etc. Nevertheless there are some attractive potentials for LMFBR application, assuming the capsule is easily retrievable and a new one easily insertable. The fuse could go in any available channel. The differences in melting points suggest that the capsule might not need to be re-opened to restore the fuse. If the antimony melting point is too low, it could be adjusted by making the fuse of a suitable binary with an x, y, Li ternary as the final absorptive mix. If the melting rate is not sufficiently determinable, then more of a "snap" action possibly could be achieved by bimetallic strips (farther removed from the core) or a thin layer of antimony which would melt to release a stainless steel slug. The slug, on dropping, would displace the molten lithium, thereby raising the lithium into the core.

Method No. 5, B_4C Pins, Pneumatic Drive

Consideration of Methods 1, 2 and 3 has contraindicated the use of lithium as a neutron absorber for shutting down the FTR. Consequently,

for the sake of comparative evaluation*, a B₄C pin bundle concept is introduced here which is similar to that of the present FTR design but with a drive connection operated by a simple pneumatic (argon) piston. The poison section would be either in or out of the core with appropriate control room indication. Intermediate positioning would not be possible. The poison assembly insertion stroke would be powered from a pressurized gas storage tank, and damping would be provided at the end of the stroke. The design of the piston would render the poison section incapable of fast withdrawal. Since design of the mechanical details of such an assembly is not within the scope of the HEDL study, further consideration was not given to the hardware. However, it is within the scope⁽¹¹⁾ of HEDL studies to relax core design requirements such as number and location of test positions. Accordingly, Method No. 5 involves a reconsideration of the assigned core positions (Figure 3).

It is proposed that the channel now labelled "OSC" and the channel labelled "Prox. OT" be changed from the present assignment as test positions to safety rod positions. These two B₄C safety rods would comprise a separate system to be called the Primary Safety System. These two new rods, having the pneumatic stroke design suggested above, would not penetrate the instrument trees as do the present rods, but they would have protective guide tubes. A hole in the vessel head would be required over the "Prox. OT" position. Because of the rather arbitrary distinction between the present primary and secondary systems, it is further proposed that the

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*See table on pages 25, 26 and 27.

"stuck-rod" criterion be applied to the newly defined secondary system, which would be comprised of all remaining scrammable rods. The design⁽¹²⁾ of the scrammable rods would be basically the same as the present in-core safety rods (such as driveline and roller-nut drive), but without spring-assisted entry. Additionally, the poison section would be comprised of tantalum* absorbers to provide further diversification and to eliminate the problem of helium generation with burnup. Helium generation would not be a problem in the proposed B₄C primary system rods because these normally would reside outside of the core. The "stuck-rod" criterion would apply to one of the three rods now labelled "SR" (Figure 3). The total strength of the newly proposed secondary appears to provide enough shutdown margin with the strongest of these rods "stuck", assuming the new primary shutdown system has failed to act. A reactivity balance of the proposed rearrangement was not within the study scope, but the total worth was calculated to be approximately -6.7% $\Delta k/k$, using all Ta and with the same v/o as the present B₄C pins.

The proposed rearrangement (Figure 5) results in a cleaner more symmetrical map. For instance, the "line" designated by PC, CR, SR, Prox.OT, SR, CR and FSR has been eliminated. By comparing Figures 3 and 5, it is possible to arrive at a summary of the trade-offs:

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*Sufficient data have been accumulated to develop confidence in prediction of swelling⁽¹³⁾ effects in tantalum.

OT	OPEN TEST ASSEMBLIES - 3
CR	IN-CORE SHIM / SCRAM RODS - 6
PC	PERIPHERAL CONTROL RODS - 6
PSS	PRIMARY SHUTDOWN SYSTEM RODS - 2
GP CL	GENERAL PURPOSE CLOSED LOOPS - 2
SPT	SPECIAL PURPOSE TEST - 2
FSR	FIXED SHIM RODS - 6
	DRIVERS - 28 INNER (ROWS 1 - 4) - 48 OUTER (ROWS 5 - 6)
	REFLECTORS - 96

NOTE: REACTOR CAPABILITY=6 CLOSED LOOPS

FIGURE 5. Modified Core Map

Added	Deleted
1. Two new primary shutdown rods. (PSS)	1.a One proximity instrumented open test. (Prox. OT)
	1.b One oscillator (or closed loop test). (OSC)
2. One new driver	2. One in-core shim/scram rod (CR)
3. Three reflectors	3.a Two peripheral control rods. (PC)
	3.b One fixed shim rod. (FSR)

The general intent of the new arrangement would be to increase the worth of the secondary by assigning to it more central and unshadowed positions to permit trading off the decrease in strength caused by the change to the tantalum absorber. Some peripheral poison has been removed and reflectors added which should increase the reflector savings and tend to flatten the power distribution. More fixed peripheral shims could be added if necessary. It is recognized that there is a desideratum of maintaining the number of rods as a fixed parameter,⁽¹⁴⁾ but this is not possible if the positions and materials are simultaneously changed. It should be noted that the total closed loop capability still remains at six although the oscillator test, if performed, would have to be run in the remaining central closed loop position.

In summary, Method No. 5 is the obvious choice of all methods considered on the basis of current technology, reliability, testability, availability, speed, worth, and cost. This method also carries with it a potential savings to the FFTF Project of almost \$500,000 by virtue of substituting two simplified drive rods for three roller-nut drives which are eliminated.

EVALUATION AND RECOMMENDATION

On the basis of the considerations of the five methods previously discussed, and by virtue of the summary presented in Table 1,^(16,17) it is recommended that further consideration of lithium as a rapid shutdown method be abandoned. To recapitulate: lithium poisoning is not state-of-the-art, its use would be astronomically expensive in the extreme; and its use might actually detract from, rather than enhance, the safety of the FTR.

To achieve diversity as well as independence, two central, pneumatically-driven, boron carbide safety rods are recommended. This method (No. 5) is seen to enhance FTR safety at less cost to the project and is the cost/effective choice therefore.

TABLE 1

EVALUATION OF ALTERNATE SHUTDOWN REQUIREMENTS

		Method #1 Primary System	Method #2 Closed Loop	Method #3 Empty Thimble	Method #5 B ₄ C Rods
FUNCTIONAL	25 1. The system should not be susceptible to the following postulated common mode failures of the present primary and secondary shutdown systems.				
	(a) Lateral movement of core relative to the head or instrument trees.	+	+	+	+
	(b) Common design or manufacturing flaw in hardware (mechanisms, drivelines or absorbers) which prevents it from performing its function.	+	+	+	+
	(c) Environmental effects and single faults.	+	-	-	+
	2. The system shall be capable of testing to demonstrate operability without significantly affecting reactor availability.	-	-	-	+
	3. The system shall have sufficient worth to shut the reactor down to zero power for all events which could simultaneously disable any other shutdown systems.	+	+	+	+
	4. The system shall act sufficiently fast to prevent the safety limit from being exceeded in the event of a fault which results in the simultaneous disability of any other shutdown systems. (NOTE: safety limit should be defined by ARD).	-	-	+	+
	5. The system shall be capable of operation up to the threshold of the hypothetical core disruptive loading.	+	+	+	+

EVALUATION OF ALTERNATE SHUTDOWN REQUIREMENTS

	Method #1 Primary System	Method #2 Closed Loop	Method #3 Empty Thimble	Method #5 B ₄ C Rods
1. The system shall not lose shutdown capability as a result of instrument tree motion.	+	+	+	+
2. The system shall be capable of being tested consistent with functional requirements	-	-	+	+
3. The minimum worth shall be 1% $\Delta k/k$, with a goal worth of 2% $\Delta k/k$.	+	+	+	+
4. The system speed of response shall prevent violent fuel failure in the event of complete loss of off-site electrical power and no action of any other shutdown system.	-	-	+	+
5. The design must be compatible with the general duct arrangement of the core, radial reflector and shield, instrument trees, IVHM, reactor heat, vessel & cavity.	+	+	+	+
6. The design must be consistent with the following coolant temperatures:	+	+	+	+
	Initial Improved Core Operation Operation			
Core Averaged Inlet Temp.	600°F	800°F		
Core Averaged Outlet Temp.	900°F	1100°F		
7. The lifetime of the in-reactor portion shall be at least one refueling cycle.	+	+	+	+
8. The system shall be designed to limit the potential for primary sodium contamination.	-	+	+	+

DESIGN

EVALUATION OF ALTERNATE SHUTDOWN REQUIREMENTS

	Method #1 <u>Primary</u>	Method #2 <u>Closed</u>	Method #3 <u>Empty</u>	Method #5 <u>B₄C Rods</u>
1. Consideration should be given to incorporating the alternate system into and/or replacing either the primary or secondary protective system.	-	-	+	+
2. State-of-the-art concepts and materials will be used where possible to minimize development.	-	-	-	+
3. Cooling will be provided by existing cooling systems	+	+	+	+
4. The system shall be capable of operation during refueling	+	+	+	+
5. The system shall not use the same design as any other shutdown system for the mechanism, drive-line or absorber.	+	+	+	+
6. The goal lifetime of the in-reactor portion shall be at least one year. The lifetime of the out-of-reactor portion shall be at least 10 years.	+	+	+	+
7. The concept will be generally applicable to LMFBR's.	+	-	+	+
8. Within the framework of the current design, selected core design requirements may be relaxed in order to adequately explore a broad range of shutdown schemes. Requirements which may be relaxed include power, flux, number and location of test positions in order to investigate trade-offs between changes in those requirements and added safety.	-	-	+	+
	<u>+7</u>	<u>+5</u>	<u>+17</u>	<u>+23</u>

OBJECTIVES

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ACKNOWLEDGMENT

The writer gratefully acknowledges the technical contributions of R. E. Keyes, D. H. Lester, O. B. Monteith, and L. D. O'Dell, and also the suggestions of D. Marinos.

APPENDIX A

PRELIMINARY FAULT TREE FFTF SAFETY ANALYSIS

(Submitted by O. B. Monteith)

PRELIMINARY FAULT TREE - FAILURE TO SHUTDOWN REACTOR - FFTF SAFETY ANALYSIS

O.B. MONTGOMERY

APPENDIX B

INDEPENDENT SHUTDOWN SYSTEMS

(Submitted by L. D. O'Dell)

WADCO
P.O. Box 1970
Richland, Washington
99352
(509) 942-1111

From Reactor Analysis Section
Date December 2, 1970
Subject INDEPENDENT SHUTDOWN
SYSTEMS

TO: D. P. Schively

cc: R. E. Heineman
P. L. Hofmann
W. W. Little
L. D. O'Dell/File
D. D. Stepnewski

The worth of four possible shutdown systems which are capable of operating independent of the existing control rod shutdown system was studied. Two of these systems involve placing an evacuated 316 stainless steel, SS, tube in the oscillator position into which either lithium or boron carbide balls could be dumped. The third system employs the replacement of sodium by lithium in a closed loop near the core center (second row of subassemblies). The last system homogeneously distributes lithium throughout the primary sodium coolant.

The core configuration used for this study was for August, 1970 with the only modification being the replacement of the oscillator by a fuel subassembly (Figure B-1). The atom densities used in the study were obtained from the Westinghouse letter FRP-238 (6/15/70). The calculations were performed at 400 MWt using 2DB in hexagonal geometry with 4-group cross sections generated by 1DX from the 26 group FTR-III design set. The cross sections were generated at both 400°F (205°C) and 1000°F (540°C). In the 2DB calculations, all movable rods were assumed to be withdrawn and an axial core-average buckling (B^2) of $6.04 \times 10^{-4} \text{ cm}^{-2}$ was used.

The first two shutdown systems are essentially the same since they both employ an evacuated tube in the oscillator position. They differ only in that the first system uses liquid lithium as the control material and the second uses boron carbide balls. A sketch of the evacuated tube is shown in Figure B-2. The composition of the liquid lithium (Li) was assumed to be 90 w/o Li^6 and 10 w/o Li^7 . The boron carbide (B_4C) balls had a diameter of 0.635 cm and the boron (B) composition was taken as 95 a/o B^{10} and 5 a/o B^{11} . In considering the packing of the B_4C balls, one third of the volume was found to be void.

The results of the calculations at 400°F and 1000°F are shown in Tables B-1 & B-2. Where Table B-1 gives the calculated multiplication constants, k_{eff} ; the peak flux, Φ ; and the peak power density, P_D . Table B-2 gives the worth or $\Delta k/k$ of the respective systems. These results include the variation in sodium and lithium densities which occur with the temperature change from 400°F to 1000°F . The number of kilograms of sodium and lithium involved in each case is given in Table B-3. This variation in temperature was not expected to appreciably effect the results and as shown in Table 2 it had virtually no effect.

In performing the calculations with the evacuated tube in the oscillator position, the core-average buckling could not be used at this position due to the presence of the void. Therefore, a buckling was calculated which was appropriate for the void. This was done by first performing transport calculations in RZ geometry to obtain the worth of a void at the radial center

of an RZ core. The two-dimensional transport theory code DOT with S⁴ and S⁸ quadratures and 4 group cross sections was employed for this purpose. The LDX code was then used in cylindrical geometry to obtain a buckling modifier, γ_{am} , for a voided region at the core radial center which would yield the same void worth as the transport calculation. This buckling modifier was then employed in the voided region in the 2DB hexagonal calculations. The buckling modifier was found to be 1.7×10^{-4} which when applied to the axial core average buckling yielded a buckling for the void of $(1.7 \times 10^{-4} \times 6.04 \times 10^{-4})$ $1.03 \times 10^{-7} \text{ cm}^{-2}$.

Larry D. O'Dell

LDO:jah

GENERAL PURPOSE CLOSED LOOPS-2

SPECIAL PURPOSE CLOSED LOOPS -2

OPEN TEST ASSEMBLIES- 3

OPEN TEST ASSEMBLY WITH PROXIMITY
INSTRUMENTATION-1

OSCILLATOR - 1

AEC RL RICHLAND WASH

DRIVERS-27 INNER (ROWS 1-4)
-48 OUTER (ROWS 5-6)

SAFETY RODS-3

IN-CORE SHIM/SCRAM RODS-4

PERIPHERAL CONTROL RODS-8

FIXED SHIM RODS-7

REFLECTORS-93

FIGURE B-1. Core Map August 1970

FIGURE B-2. Sketch of Evacuated Tube in Oscillator Position

Table B-1. CALCULATED EIGENVALUES, PEAK FLUXES, AND
POWER DENSITIES FOR ALTERNATE SHUTDOWN SYSTEM STUDY

	TEMP = 400°F			TEMP = 1000°F		
	k_{eff}	Λ_ϕ (n/cm ² - sec)	Λ_{PD} (MW/liter)	k_{eff}	Λ_ϕ (n/cm ² - sec)	Λ_{PD} (MW/liter)
(1) Base Case Fuel in OSC* Position	1.071	6.789 $\times 10^{15}$	0.7209	1.065	6.788 $\times 10^{15}$	0.7191
(2) Sodium in OSC position	1.060	6.507 $\times 10^{15}$	0.7166	1.054	6.494 $\times 10^{15}$	0.7170
(3) Evacuated** Tube in OSC Position	1.065	6.641 $\times 10^{15}$	0.7229	1.059	6.638 $\times 10^{15}$	0.7234
(4) Tube of Lithium in OSC position	1.024	6.525 $\times 10^{15}$	0.7718	1.019	6.510 $\times 10^{15}$	0.7674
(5) Tube of Boron Carbide Balls in OSC position	1.019	6.496 $\times 10^{15}$	0.7866	1.013	6.605 $\times 10^{15}$	0.7848
(6) Lithium replacing Sodium in closed loop	---	---	---	1.032	6.789 $\times 10^{15}$	0.7720
(7) Fuel in OSC position; Lithium homogeneously distributed in primary coolant	1.042	6.812 $\times 10^{15}$	0.7284	1.038	6.806 $\times 10^{15}$	0.7275

* OSC is the oscillator

** Used a buckling in the voided region of $1.7 \times 10^{-4} \times 6.04 \times 10^{-4} \text{ cm}^{-2}$.

TABLE B-2. CALCULATED WORTHS OF ALTERNATE SHUTDOWN SYSTEMS

	Temp. = 400°F	Temp. = 1000°F
	$\Delta k/k$	$\Delta k/k$
(1) Sodium in OSC* position [(2) - (1)]**	-0.010	-0.010
(2) Evacuated Tube in OSC position [(3) - (1)]	-0.006	-0.006
(3) Tube of Lithium in OSC position [(4) - (3)]	-0.038	-0.038
(4) Tube of Boron Carbide Balls in OSC position [(5) - (3)]	-0.043	-0.043
(5) Lithium replacing Sodium in Closed Loop [(6) - (1)]	--	-0.031
(6) Fuel in OSC position; Lithium homogeneously distributed in primary coolant [(7) - (1)]	-0.027	-0.025

* OSC indicates oscillator

** Refers to cases listed in Table B-1

TABLE B-3. KILOGRAMS OF SODIUM AND LITHIUM
INVOLVED IN EACH SHUTDOWN SYSTEM

	TEMP. = 400°F		TEMP. = 1000°F	
	Sodium	Lithium	Sodium	Lithium
(1) Sodium in OSC* position	8.80	0.0	7.95	0.0
(2) Evacuated Tube and surrounding sodium in OSC position	1.71	0.0	1.54	0.0
(3) Tube of lithium and surrounding sodium in OSC position	1.71	3.71	1.54	3.50
(4) Lithium replacing sodium in closed loop	---	---	4.86	2.99
(5) Lithium homogeneously** distributed in primary coolant	401.	2.53	362.	2.38

* OSC stands for oscillator

** Core only

APPENDIX C

LITHIUM ADDITION
IN FFTF CRITICALITY ACCIDENT

(Submitted by D. H. Lester)

WADCO
P.O. Box 1970
Richland, Washington
99352
(509) 942-1111

From . SODIUM TECHNOLOGY
Date . November 17, 1970
Subject . Lithium Addition in
FFTF Criticality Accident

TO: Dixon Shively

cc: WF Brehm
VF FitzPatrick
VJ Putkauskas
WR Wykoff
File

In response to your request for information regarding use of ^6Li as a neutron poison in the event of a gross control rod failure, I have compiled the following:

1. Cost of ^6Li

I have been unsuccessful in obtaining the cost of ^6Li enriched to 99%. However, a call to MSAR did yield an approximate figure for metallic industrial grade Li. They said it should be about \$11 per pound. Therefore, the 6000 lbs. required would start at about \$66,000. However, the MSAR people were certain that the enriched (and chemically pure) Li would be many times more expensive. In short, the ^6Li will cost into hundreds of thousands of dollars. Exact cost information of ^6Li may possibly be available from the following sources:

American Potash
ORNL
NASA Lewis (Cleveland)

2. Recovery of Li from Na

It appears that the only possibly feasible engineering method for recovering the 6000 lbs. of Li from the reactor primary Na would be a hydriding - cold trapping method. Hydrogen would be added to the system causing LiH to form. The LiH could then be cold trapped.

The cold trapping would require 8000 to 10,000 gallons of crystallizer volume. I estimated this on the basis of trapping Na_2O and NaH with cold traps. The required cold trap capacity for Li recovery is more than 10 times the present cold trap volume in the reactor primary. A substantial capital investment (greater than \$500K) would be represented in the cold trap equipment alone. Equipment for hydriding, etc., would be separate.

I would say the feasibility of ^6Li recovery is doubtful.

3. Space and additional expense

The tankage required to maintain liquid Li in a ready state would take up a great deal of space. It's possible that the tank would have to be in containment to be as close to the core as possible. The capital cost of the tank (see Bill Brehm's memo attached) would be high since exotic materials would possibly be needed.

4. Materials Problems

I have asked Bill Brehm, who has had experience in Li work, to compile some comments especially on the materials problems. His memo is attached and is self explanatory. Note that Jack DeVan will be here tomorrow and may be able to help you further.

I recently encountered an additional reference which may be of use:

L.G. Hays, "Surface Damage From High-Velocity Flow of Lithium,"
J. Materials Vol. 5 p 666 (1970).

5. Dynamics

Has anyone considered whether the Li can be added to the reactor fast enough in comparison to the rate of excursion? I would assume that very high flow rates would be required.

If you require any further information feel free to contact either myself or Bill Brehm. I am on 3652 and Bill is on 3009.

D. H. Lester
Systems Engineering

DHL:ph
enc.

WADCO
P.O. Box 1970
Richland, Washington
99352
(509) 942-1111

SODIUM TECHNOLOGY
November 16, 1970

TO: D. H. Lester

cc: DIJ Shannon
RR Borisch
WFB File

COMMENTS ON LITHIUM USE

1. Is the high degree of isotopic separation all that necessary, particularly when it is anticipated that the final mixture of lithium and sodium will be 0.6% Li?
2. Lithium melts at 350°F, so the storage tank will have to be heated. Lithium may corrode stainless steel even at that low temperature, so a Cb-1 Zr liner in the storage tank may be needed.
3. Lithium may severely corrode stainless steel. Also, since Li_2O is more thermodynamically stable than PuO_2 or UO_2 , lithium will probably react with fuel if it comes in contact. This will make quite a mess. It is anticipated that in the event that lithium is dumped in to stop a runaway reactor, the core, core barrel, support structure and maybe the vessel liner, instrument tree, and fuel handling machine will have to be replaced. The vessel, pumps, and piping could probably be saved. Remember though, that by the time the situation became so desperate as to necessitate the lithium dump, probably most of the in-vessel hardware would have been damaged beyond repair anyway.
4. The high affinity for oxygen means that the oxygen or oxide content of the lithium is not too critical, lithium attacks by dissolution and by reacting with dissolved oxygen in the structural metal. Lithium left to stand in air forms a dark grey nitride on the surface. The upshot of this is that continuous purification of Li in the storage tank may not be necessary. The cover gas should be pure, however.
5. Lithium does not react as violently with water as does sodium, however lithium fires, once they start, are almost impossible to put out.
6. More information, including problems of isotopic separation, can be obtained from:

Jack DeVan - ORNL 615-483-6923 (He will be here 18 Nov.)

Emil Kovacevich - Federal Building 6-4026

Gene Hoffman - GE - Evendale, Ohio (DeVan will know his phone number)

and reports DMIC-227 and ORNL-3424.

*also Carbon Science memo
NAB - Lewis*

W. F. Brehm

W. F. Brehm
Systems Development

WFB:ph

APPENDIX D

LITHIUM INJECTION FOR FTR SHUTDOWN

(Submitted by R. E. Keyes)

WADCO
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Richland, Washington
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Engineering Analysis
Nov. 16, 1970
LITHIUM INJECTION FOR
FTR SHUTDOWN

Attachment: Calculations/
RE Keyes

To: D. P. Schively

From: R. E. Keyes

cc: JF Fletcher
RE Keyes/file/LB

Two methods of shutdown, independent of control rod insertion, have been examined. One was to inject lithium into an empty thimble that would be located in an available core channel. The other was to inject liquid lithium into the closed loop tube employing a parallel Li system which replaces the ex-reactor system.

Lithium Discharge to Thimble

This system is simple but would eliminate one core position from any other usage. Figure 1 is a diagram of this system. It operates with a pressurized tank of argon being discharged by explosive opening of a valve. The discharged gas pressurizes a tank of lithium liquid. The lithium in turn is discharged into a thimble in the core via a burst disc. The thimble is vented via another burst disc. Gas circulation below the lithium burst disc may be required in order to monitor this void space.

Piggy-Back on Closed Loop System

This system utilizes the closed loop system as a means for injecting lithium into the FTR core. See Figure 2 for diagrammatic arrangement. As conceived, the parallel "piggy-back" lithium loop is fully charged at all times. Cooling is by a coil in the IHX.

The system is to perform in the following manner:

1. Upon signal an explosive valve is opened to discharge 1230 psi argon into 2.5 ft³ lithium charge tank. Approximately 2.3 ft³ of lithium is necessary to displace the sodium in the closed loop tube. The gas pressure would be about 800 psi.
2. Simultaneously with the above action the lithium circulating pump is started.

3. At a time delay after action 1, above, the closed loop tube outlet shut-off valve is closed automatically. The shut-off timing must be such that a minimum of 2.3 ft³ of Li is discharged from the lithium tank but not enough that charge gas enters the lithium loop.
4. After a time delay, or possibly simultaneously, with the previous action, the lithium valve branching from the closed loop tube outlet line opens. By this action and the previous one, the loop consisting of the parallel piggy-back lithium system and the closed loop tube passage (in and return) should be practically fully lithium charged. A complete lithium loop could then function to remove decay heat from the test for the necessary decay period.

Some important characteristics of the two systems are as follows:

- . The Li discharge into a thimble system can insert 2 gallons, 8 lbs., of lithium into a core position in 0.5 seconds.
- . The lithium piggy-back on the closed loop system can inject lithium into the core as tabulated below:

<u>Flow @ 100 psi ΔP Test</u>	<u>Time</u>
100 GPM	1.2 sec
50 GPM	2.3 sec

The volume of lithium in the core portion of the tube is 228 in³, 1 gallon or about 4 pounds.

REK:vf

LITHIUM DISCHARGE TO THIMBLE

Fig. 1

PIGGY BACK LITHIUM ON CLOSED LOOP SYSTEM

Fig. 2