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**HAZARDS SUMMARY MEMORANDUM - SAVANNAH RIVER REACTORS
 THE PRODUCTION OF TRITIUM USING TUBULAR FUEL ELEMENTS**

D. F. Babcock and R. L. Menegus
 Reactor Engineering Section
 Wilmington, Delaware

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HAZARDS SUMMARY MEMORANDUM - SAVANNAH RIVER REACTORS
THE PRODUCTION OF TRITIUM USING TUBULAR FUEL ELEMENTS

INTRODUCTION

The Savannah River reactors were operated initially for the production of plutonium, and used slug-type natural uranium fuel elements. Recently one reactor was converted to the production of tritium, and other reactors will be converted soon. Slug-type elements (of enriched uranium-aluminum) were charged into this reactor in order to reduce to a minimum the development effort required before the shift to tritium was made. It was recognized, however, that the slug elements would be deficient in that they would give a low yield of tritium per atom of uranium-235 destroyed because of the large parasitic capture of neutrons by aluminum. Also the production rate of tritium would be low because of the small amount of surface available for the transfer of the fission heat.

Both of these shortcomings will be reduced materially by the substitution of tubular elements for the slugs now employed. The development of this type of element has progressed so that a full reactor loading of tubular fuel elements is contemplated for early 1957. The special hazards related to the production of tritium using tubular fuel elements are described in this memorandum which has been written as a supplement to a report entitled "Reactor Safety Determination - Savannah River Plant" (DPW-56-106), one section of which described the hazards associated with the production of tritium from slug elements.

SUMMARY

New tubular-type fuel elements for the production of tritium have been developed, thoroughly tested outside of a reactor and are now being exposed to the full neutron flux of a Savannah River Reactor. If these pilot tests prove satisfactory, the current plans call for converting an entire reactor to this type of fuel element early in 1957. The advantages to be gained by converting to tubular-type elements from the slugs now being used are:

- 1) The power level can be increased from the present expected limit of about 1200 MW to 1800 MW, or perhaps even higher.
- 2) The tritium produced per megawatt day will be increased by about 15%* as a result of the decreased neutron loss to the aluminum contained in the assembly.
- 3) The fuel elements will operate at a lower central metal temperature (250° vs. 350°C).
- 4) There are fewer (3 vs. 4) parallel passages for the flow of coolant. This modification improves the efficiency of the flow meters.
- 5) The fuel tubes are cooled from both sides whereas the slugs are cooled only on one side. A reduction in water flow to any channel is partially compensated for by the dumping of heat to the coolant channel on the opposite side of the element.
- 6) Fewer elements will be required because of the longer cycle for tubular elements.

The chief disadvantage of the tubular fuel element is the possible reduced safety in the event of a meltdown of a significant number of fuel elements. In the slug case the interspersing of target and fuel along a water channel almost precludes any major separation of fuel and target should a meltdown of fuel occur. For the tubular element, the target and fuel are separated (see Fig. 1) making it possible for the fuel to melt and separate from the target. In either case, the melting of the fuel will separate the fuel from the control elements and as indicated in DPW-56-106, this separation might lead to a nuclear explosion.

In view of the above, it is probable that if severe meltdown of the tubular assemblies occurs, the chance of a nuclear explosion is greater than with slug-type elements. On the other hand the increased surface and increased coolant flow available with tubular elements greatly reduces the chance that meltdown will occur.

* At 25% burnup for each type of element.

D. F. Babcock

R. L. Menegus
Reactor Engineering Section

DISCUSSION

1) Description of Fuel Elements

a) Slug Type Element (Mark VIII)

In order that the Savannah River reactors could be converted rapidly from the production of plutonium to the production of tritium, a fuel element was developed which comprised fuel slugs of enriched uranium-aluminum interspersed with target slugs of lithium-aluminum. A complete description of this fuel element (Mark VIII), together with a description of the hazards associated with its operation, is given in DPW-56-106. It was recognized that this element was deficient both as to ultimate power output and as to the amount of tritium that it would produce per megawatt day. On the other hand, the simplicity of this type of element allowed a rapid change-over from the production of uranium slugs to the production of slugs of enriched uranium-aluminum and lithium-aluminum. One reactor is currently operating at the Savannah River Plant using Mark VIII fuel elements for the production of tritium. No unexpected phenomena have been observed in the operation of this reactor.

b) Tubular Fuel Elements

Many of the shortcomings of a slug-type element have been reduced or eliminated by the development of a tubular fuel element which comprises an outer target tube of lithium-aluminum, two intermediate fuel tubes of enriched uranium, and an inner housing tube of aluminum. Both fuel and target tubes are sheathed with pure aluminum in order to reduce the possible contamination of the moderator with radioactive products. Passages between the tubes allow a flow of sufficient cooling water so that local boiling of the coolant will be prevented. A diagrammatic view of this fuel element (Mark VI-A) is given in Fig. 1.

The fuel tubes are produced by the extrusion of a composite hollow billet which comprises a tube of enriched uranium-aluminum surrounded top, bottom, inside and outside with pure aluminum. This hollow billet is then extruded through a suitable die to produce the fuel tube to which appropriate end fittings are welded. The target tube is manufactured in much the same way.

A fuel tube of similar design to that described above was developed in conjunction with the program for the production of uranium-233 from thorium. Since only a minimum of development effort was required to combine this tube with a slug-type target of lithium-aluminum into a fuel element (Mark VI) that had properties superior to that of a slug-type element, it was decided to proceed along this line as an interim development. As soon as the problem of the extrusion of target tubes could be solved, a shift to the manufacture of the combined tubular target and tubular fuel element was planned.

In the discussions that are given in this memorandum comparing slug and tubular elements, the intermediate case of the Mark VI element was omitted. All comparisons are between the slug-type Mark VIII and tubular fuel and target Mark VI-A elements.

2) Advantages of Mark VI-A Elements

The power output attainable from a Mark VIII fuel element is believed to be no greater than about 1200 MW. At powers above this figure, local boiling of the coolant will occur. While we cannot state that local boiling must be avoided, the margin between local boiling and eventual burn-out is small. We would like to keep this zone as a safety margin. For Mark VI-A the power can be increased to above 1800 MW as a result of a) an increase in the surface area from 12 sq. ft. for the slug element to 35 sq. ft. for the tubular element and b) an increase in the width of the coolant passages so that the water flow may be increased from 200 gpm to 300 gpm.

The amount of tritium that is produced per megawatt day will be increased by about 15%. This results from the decreased parasitic losses of neutrons to capture by the aluminum.

The tubular fuel elements have a thickness of only about 0.15 in. as compared with 1.08 in. for slugs. This reduces the heat path and thus reduces the maximum temperature of the metal within the fuel element from about 350°C to about 250°C.

There are only three parallel passages for the flow of coolant through a tubular fuel element, as compared with four for the slug-type element. Since only the total water flow through a fuel element is measured, a lesser precision in flow measurement is required for Mark VI-A in order to know whether or not a reduction in flow in any channel has taken place. In addition to the above, the fuel tubes are cooled from both sides, whereas, the slugs are cooled from only one side. Even though the flow through one channel becomes reduced, the fuel element may still be adequately cooled, since a major portion of the heat will be dumped to the coolant channel on the opposite side of the element.

A longer exposure in a reactor is expected for a Mark VI-A element than for the Mark VIII because of its lesser reactivity change with time. (See Graph 1). In the Mark VI-A element the target is outside the fuel and is exposed to a higher neutron flux than is the target of Mark VIII, which is at about the same flux as the fuel. Because of this, the target, with a higher capture cross section, burns at a higher rate in the Mark VI-A element.

The Mark VI element has a reactivity change much like that of the Mark VIII, because the target is in a region of low neutron flux.

3) Test Work Leading to Installation of Tubular Elements

The following test work has been conducted with the objective of gaining knowledge concerning the performance of a tubular enriched uranium charge prior to loading the entire reactor with this type of element.

a) Fuel-target assemblies of both the Mark VI and VI-A types were inserted into the Process Development Pile (PDP), and their neutron multiplications were measured. Adjustments were then made in the lithium concentration in order to give the desired initial buckling of approximately 800 microbucks.

b) Both dummy and actual fuel assemblies were tested in the hydraulic laboratory in order to determine the behavior of this new type of fuel element as to erosion, vibration damage, etc. under simulated reactor hydraulic conditions. With the help of these tests, the design of the end fittings was modified to reduce the amount of hydraulic noise that was picked up by the flow monitoring devices.

c) In addition to the standard metallurgy tests, some of the fuel elements were deliberately pinholed and exposed to water at 150°C. Corrosion rates were found to be no different than have been experienced with pure aluminum.

d) Fuel elements were placed in the PDP and the D₂O removed from various channels in order to determine the change in reactivity in the event that the fuel elements become so hot that the coolant or moderator boils. The results obtained are shown in the following table:

COOLANT AND MODERATOR EXPULSION TESTS

	Flat Zone	Change in k Buckled Zone	Reactor
<u>Enr. U-Li Slug Loading (Mark VIII)</u>			
All D ₂ O Expelled from the Assem.	-1.0%	-2.5%	-1.3%
<u>Enr. U Tube-Li Slug Loading (Mark VI)</u>			
D ₂ O Expelled from Fuel Channels	-0.9%	-1.4%	-1.0%
All D ₂ O Expelled from the Assem.	-6.0%	-4.2%	-5.5%
<u>Enr. U Tube-Li Tube Loading (Mark VIA)</u>			
D ₂ O Expelled from Fuel Channels	0.7%	0.4%	0.6%
D ₂ O Expelled from Central Channel	-1.6%	-2.0%	-1.7%
All D ₂ O Expelled from the Assem.	-0.9%	-1.6%	-1.1%
<u>Natural U Slug Loading (Mark I)</u>			
Moderator Expelled Between Assem.	-0.013%/ft ³	-	-0.013%/ft ³
D ₂ O Expelled from Fuel Channels	0.08%	-0.12%	+0.03%

In addition to the water expulsion experiments, test work is in progress on the present production loading of enriched uranium slugs. The temperature coefficients of reactivity have been determined by oscillating the reactivity of the production reactor with a cycle time of several seconds and measuring the response. By this means it has been determined that the fast-responding metal temperature coefficient of reactivity is -1.3×10^{-5} k/°C. This is about the same as for natural uranium. Formerly, we feared that this coefficient might be as low as zero in the case of enriched uranium. The moderator coefficient of reactivity, which is relatively slow-acting, was measured to be -3.5×10^{-4} k/°C for enriched uranium slugs. This is higher than for natural uranium slugs. As yet no measurements have been made of the temperature coefficients of reactivity of tubular elements.

e) At present, approximately 20 Mark VI and two Mark VI-A fuel assemblies are being exposed in one of the production reactors as a pilot test. If these tests indicate any potential difficulty, modifications to the fuel assemblies may have to be considered.

4) Reactor Hazards

a) Meltdown and Collapse of Fuel

The collapse of any fuel element by melting is most improbable when an adequate coolant flow is maintained. We believe that the maintenance of coolant flow at power is the mainstay of safe operation. Much experience and calculation serve to corroborate this opinion concerning the importance of this one feature in plant operation.

Accordingly, continued efforts have been directed toward assessing means of maintaining the coolant flow without the slightest interruption, detecting any reduction in flow if it occurs, and estimating the probable damage if a sudden large flow reduction occurs. Emergency operating procedures are instituted for most foreseeable accidents. If these efforts are successful, a general collapse of the fuel in the tubular assemblies will never occur. Other accidents, such as the introduction of large increases in reactor neutron multiplication, are still possible. The steps taken in the plant design and the procedural safeguards used to prevent such occurrences are explained in DPW-56-106.

b) Critical Temperatures in the Reactor

When considering new fuel assemblies, or before raising the operating power level, our practice has been to survey the proposed operation along several lines of attack. This somewhat arbitrary division of the survey aims toward estimating the various critical, intensive factors in the reactor. Most of these intensive factors are local temperatures. Others are stresses, radiation fluxes, or pressures.

In other words, before any new fuel element is tried, or before the power is raised above a previously piloted level, the following critical temperatures are calculated, and some are measured, for normal operation and also for conditions prevailing in the event of a partial stoppage of the coolant flow. (A partial stoppage might occur, for instance, if one coolant pump-motor combination fails).

- 1) Sheath temperature in the fuel.
- 2) Internal metal temperature in the fuel.
- 3) Bulk coolant temperature leaving the reactor tank.
- 4) Local moderator temperature in the moderator space.
- 5) Shield temperature.
- 6) Coolant temperature leaving any single fuel assembly.

The enriched uranium tubular fuel assemblies have been designed with the above temperature limitations in mind. Considerable operating experience has been gained in establishing temperature limits that are safe, and these are incorporated in the Technical Standards.

1) Sheath Temperature

The sheath temperature of a tubular element is reduced below that of the slugs by reason of the increased area for heat transfer. At the present time we are piloting enriched uranium-aluminum slugs at approximately 160°C on the aluminum sheaths. We do not plan to operate the enriched uranium tubes at so high a temperature.

As of September 15, 1956, we have had four slug failures out of a total of 3,200,000 slugs exposed. Three of these failures occurred in slugs that are built with an internal coolant passage designed to lower the metal temperature. The fourth occurred in a normal solid slug. All four slugs were of natural uranium, and all failures were attributed to poor welds that eluded the inspection system. The sheath temperatures were in the range of 100-160°C. No permanent damage was detected as a result of these failures. The background radiation went up several fold in some of the pipes but was brought back to normal by the purification system and the decay processes. Had these failures not been detected, it is possible that the coolant flow to the assembly could have been blocked and one or more slugs in a single fuel element would have melted.

A more serious type of failure associated with reactor operation at high heat flux and high sheath temperature is heat transfer burnout. This phenomenon has been studied under the Columbia University Contract to try to predict the conditions under which it occurs. In general, burnout occurs as a result of the formation of a continuous insulating blanket of steam on the surface so that the heat transfer rate falls

rapidly. The metal temperature rises until melting disrupts the clean geometry of the fuel element. Burnout, at high heat flux, is prevented by supplying coolant at high velocity, low temperature, and high static pressure. The large heat transfer area available from a tubular fuel element (35 sq. ft. vs. 12 sq. ft. for slugs) should increase the heat liberated before burnout by about 50%.

Burnout is perhaps the worst possible result of a reduction of the coolant flow. Considerable safety factor against burnout and melting is maintained. We normally design with a safety factor of over two* ; that is, the predicted burnout heat flux is over twice as high as the operating heat flux at rated coolant conditions. The minimum stable coolant flow with constant heat flux is then usually somewhat more than 50% of rated coolant flow. If the flow decreases to a lower figure, steam blanketing follows and burnout occurs.

2) Internal Metal Temperature

Internal metal temperature at steady power and adequate coolant flow is not a problem in the case of enriched uranium tubes, for the thermal conductivity of uranium-aluminum alloy is very high and consequently the metal temperature is relatively low (less than 350°C for slugs and 250°C for tubular elements). A power excursion must be guarded against no matter what type of fuel is used. Thus far, we have had no excursion that could be called a hazard. On several occasions, the nuclear power level rose several percent above the set point of the safety circuits, and the safety rods were inserted automatically and quickly as programmed. The temperature never has approached the melting point of the fuel.

3) Bulk Coolant Temperature

The temperature of the bulk coolant leaving the reactor tank and entering the pumps is limited because of possible cavitation at the pump-inlets. A high temperature at the pump inlet could cause the flow to drop off with consequent damage to the fuel charge. Tests have been run with hot coolant under nuclear shutdown conditions to determine this cavitation temperature limit, which varies with pump flow. We now operate at 5°C below the average pump cavitation cutoff that was measured under Test Authorization TA 1-399. In addition, if the coolant temperature approaches closer than 8°C of the cutoff value, measurements are made frequently of the pump base vibration and motor electrical current for indications of incipient cutoff.

Before the power level of any fuel charge is raised above 1400 MW, the coolant flow must be increased and its temperature decreased by extensive equipment changes. We are going to

* Some small scale tests may in the future be run with a safety factor as low as 1.7.

6) Assembly Effluent Temperature

Single fuel assemblies may discharge coolant at somewhat higher temperatures than the average. This is due, of course, to the statistical fluctuation that accompanies any operation with a large number of units. All fuel assemblies are monitored, and we will not allow the average coolant temperature of any six adjacent assemblies to exceed 110°C even if one coolant pump fails. The normal operating temperature of the coolant from any six assemblies, without any failed equipment, will be below 100°C .

The establishment of 110°C as the upper limit insures that transient boiling will not occur in the moderator space even if one pump fails, for the boiling point at the tank bottom is 114°C .

c) Reactor Instrumentation

In addition to continual surveillance of the critical temperatures described above, safe operation requires that the flow, temperature, and activity monitor systems function to shut down the reactor in the event of any failure in the coolant circuit. If the nuclear reaction is stopped in a matter of two seconds whenever the flow is reduced for any reason whatever, the use of enriched uranium fuel involves no more reactor hazard than the use of natural uranium. There are, however, added handling problems with enriched uranium outside the reactor.

During the past two years several improvements have been made in the flow and temperature monitoring instrumentation, and further work is proceeding. The coolant radioactivity monitoring system, on the other hand, cannot now be considered adequate as a means of locating failed fuel elements. In fact, the four failed slugs mentioned previously were located by routine observation of the flow and temperature monitors before definite indications were obtained from the activity monitors. Later, the activity of the gases liberated by the moderator was found to have increased significantly as a result of the slug failure. Accordingly, we are pursuing the development of gas activity monitors as a means of determining the existence of a fuel failure, along with development of coolant activity monitors. Discriminating beta and gamma detectors, located in either the gas or liquid systems, show promise of detecting small amounts of fission products in the rather high background of moderator activity due to N^{16} , O^{19} , Co^{60} , Mn^{56} , A^{41} and others.

The flow monitor system is judged to be quite satisfactory for its designed purpose. The "Very Low Flow" switch on each fuel assembly is set to fire at a maximum flow reduction of 6%. However, monitoring for very low flow is necessary but not sufficient to guard against any flow reduction. Tests have

shown that steam formation at the coolant discharge ports from the assembly can increase the ports' pressure drop, which with a single-phase is a reliable measure of flow. The current plan is to install additional switches, similar to the very low flow switches, and to have these actuated by high pressure drop. Then the assembly pressure drops must remain in a narrow band of values if the reactor is to remain at power. Otherwise it is shut down automatically. There is confidence that the doubly-limited flow bandwidth scheme is practical and that any significant deviation in flow will be detected.

Major improvements have been made in the performance of the coolant temperature monitor. An increase of 3°C in the temperature of the effluent from any fuel position sounds an alarm calling for increased surveillance by the operators. An increase of 4°C initiates automatically a gradual reduction of reactor power.

Recent plant experience has shown that the reactors are shut down once or twice per month by spurious low flow signals. During the last year, there were 95 unscheduled shut-downs caused by spurious neutron level signals, spurious low flow signals, human error in manipulating the instruments, and necessary repair work.

We believe that these monitoring systems constitute our most efficient safeguard against hazardous flow reduction. However, there can be no practical, mechanical substitute for constant, intelligent watchfulness. A high order of performance by the operators has contributed to the successful operation of the monitor systems.

ENRICHED URANIUM FUEL-TARGET ASSEMBLIES

MARK VIII
Enriched U Slug Loading

Max. Power = 1200 MW
 Prod. Factor = 0.011 gT/MWD
 Burnup of U-235 = 25%

MARK VI
Enriched U Tube Loading

Max. Power = 1600 MW
 Prod. Factor = 0.011 gT/MWD
 Burnup of U-235 = 25%

MARK VIA
Enriched U Tube Loading

Max. Power = 1800 MW
 Prod. Factor = 0.012 gT/MWD
 Burnup of U-235 = 50%