TRIGA LOW ENRICHMENT FUEL

A. Gietzen

General Atomic
San Diego, California

BACKGROUND

Sixty TRIGA reactors have been sold and the earliest of these are now passing twenty years of operation. All of these reactors use the uranium-zirconium hydride fuel (UZrH) which provides certain unique advantages arising out of its large prompt negative temperature coefficient, very low fission product release, and high temperature capability. Eleven of these sixty reactors are conversions from plate fuel to TRIGA fuel which were made as a result of these advantages.

With only a few exceptions, TRIGA reactors have always used low-enriched-uranium (LEU) fuel with an enrichment of 19.9%. The exceptions have either been converted from the standard low-enriched fuel to the 70% enriched FLIP fuel in order to achieve extended lifetime, or are higher powered reactors which were designed for long life using 93%-enriched uranium during the time when the use and export of highly enriched uranium (HEU) was not restricted.

The advent of international policies focusing attention on nonproliferation and safeguards made the HEU fuels obsolete. General Atomic immediately undertook a development effort (nearly two years ago) in order to be in a position to comply with these policies for all future export sales and also to provide a low-enriched alternative to fully enriched plate-type fuels. This important work was subsequently partially supported by the U. S. Department of Energy.

The laboratory and production tests have shown that higher uranium densities can be achieved to compensate for reducing the enrichment to 20%, and that the fuels maintain the characteristics of the very thoroughly proven standard TRIGA fuels. In May of 1978, General Atomic announced that these fuels were available for TRIGA reactors and for plate-type reactors with power levels up to 15 MW with GA's standard commercial warranty.

TRIGA FUELS

The standard types of TRIGA fuel are listed in Table 1. The 70% and 93% enriched fuels are no longer available for sale and have been replaced by the "LEU" versions as designated in the table. TRIGA fuel with 12 wt % uranium has been proven through successful reactor operation for over a decade.

Previous work on UZrH fuels during the SNAP reactor program had developed the technology up to 20 wt % uranium and found no indication of this being a limit. The program at General Atomic extends this technology to 45 wt % and has also shown no indication of this being a limit at this time. It is of interest to note that 45% uranium by weight is still less than 20% by volume.

The 20 wt % fuel which replaces the 70% enriched FLIP fuel has a total U-235 loading which is less than that in the FLIP fuel; however, it retains very long lifetime capability and represents a small extension of the very well proven UZrH technology. This 20 wt % fuel is applicable to the 1 to 3 MW range in either a standard TRIGA element configuration or in a 4-rod cluster configuration for direct replacement of plate-type elements. In the case of a plate fuel replacement, the TRIGA 4-rod cluster contains 2 to 3 times the amount of U-235 contained in plate-type elements.

The 45 wt % fuel is applicable to reactors of 5 MW and above. The amount of uranium in this fuel was selected to give essentially the same U-235 loading (and therefore core lifetime) as in the previously used fully enriched TRIGA fuels. In a 16-rod cluster configuration, which can be directly substituted for a plate-type element, the amount of U-235 per cluster is 3-1/2 to 5-1/2 times as much as is contained in the plate-type element it is designed to replace.

DEVELOPMENT PROGRAM FOR HIGH U-ALLOY FUELS

The laboratory and production tests of fuels up to 45 wt % are complete. In-core tests of production elements for thermal cycling and pulsing tests have been underway since April of 1978. The extensive test program included metallographic examinations, fission product release measurements, fuel thermal cycling stability tests, material property measurements, and production demonstration. Analysis has been completed to determine core characteristics, particularly the prompt negative temperature coefficients and neturon flux levels.

The extensive metallographic, electron microprobe and X-ray diffraction examinations have shown that the more highly loaded alloys contain no significant differences in structural characteristics when compared with the standard 8.5 and 12 wt % fuels. The phase distribution and homogeneity are excellent and these factors, coupled with the grain structure observed, support expectation of excellent long-term irradiation behavior.

The measured fission product release and physical properties show very suitable characteristics up to 45 wt %. The fission product release experiments were conducted to temperatures up to 1100°C and showed very low release fractions (about 10^{-4}) which is characteristic of the standard TRIGA fuels. In the course of these measurements it was learned that for certain grain structure characteristics, the release fraction could be as much as two orders of magnitude lower, even for uranium contents of 45 wt %.

Thermal cycling tests show that the ZrH matrix stabilizes the fuel material such that it is dimensionally stable when repeatedly cycled through the uranium phase change temperature of about 680°C.

TABLE 1

TRIGA FUEL TYPES

Description	U Content (wt %)	Enrichment (%)
Standard Fuel (8.5-20)	8.5	20
ACPR[a] (12-20)	12	20
FLIP[b] (8.5-70)	8.5	70
High-Power (10-93)	10	93
FLIP-LEU (20-20, replaces 8.5-70)	20	20
High Power-LEU (45-20, replaces 10-93)	45	20

[a]ACPR - Annular Core Pulsing Reactor
[b]FLIP - Fuel Lifetime Improvement Program

The preliminary nuclear design and analysis has shown that the prompt negative temperature coefficient for the 20 wt % uranium is about the same as for standard fuel. The value is slightly lower for 45 wt % uranium, however it is still large when compared to other fuel types. The neutron flux levels in the reflector regions and in in-core flux traps are approximately equal to those for cores with standard TRIGA fuel or for cores using HEU plate-type fuel.

Reactor testing of production elements includes both 20 and 45 wt % fuels being tested in the TRIGA Mark F reactor at General Atomic. The principal objective of these tests is to demonstrate the fuel stability for thermal cycling from ambient to operating temperatures. A total of 600 cycles has been completed to date and no adverse conditions noted. An irradiation test of a standard 16-rod cluster configuration is being designed for insertion into the 30 MW ORR Reactor at Oak Ridge, Tennessee.

APPLICATION OF TRIGA LEU FUELS

As previously mentioned most TRIGA reactors already used low-enriched fuel and will continue to do so in the future. The higher uranium content TRIGA fuels will be applied to all future sales of TRIGA reactors ($\sim$2 MW or higher) and to future sales of fuel to those existing TRIGA reactors which use HEU fuel. The most significant potential use, in keeping with the objectives of the reduced enrichment fuels program, is as a replacement for existing plate-type HEU fuels. The TRIGA fuel is available in 4- and 16-rod clusters which can directly replace plate-type fuel in existing reactor structures. The principal characteristics of TRIGA cores are given in Table 2.

TABLE 2

APPROXIMATE CHARACTERISTICS OF FORCED FLOW TRIGA-LEU CORES

	15 MW	10 MW	5 MW	2 MW
Number of Fuel Clusters	29	30	25	25
Fuel Pins/Clusters	25	16	16	4
Pin Nominal OD (in.)	0.5	0.5	0.5	1.3
Enrichment (%)	20	20	20	20
Wt % U	45	45	45	20
U Loading (kg U-235/Cluster)	1.38	0.88	0.88	0.44
Initial Excess Reactivity (%)	7	8	7	7
Control System Worth (%) Total	13	14	14	9
With Max. Rod Out	8	8	8	7
Coolant Flow Rate (gpm)	8500	500	2600	1000
Core Life				
(MW Days)	7000	4100	2700	1400
(Calendar years @ 20% duty cycle)	6.8	5.6	7.4	9.5
Peak Thermal Flux				
Core	8×10^{13}	8×10^{13}	5×10^{13}	1.5×10^{13}
Core (Central Water Hole)	3×10^{14}	3×10^{14}	1.7×10^{14}	7×10^{13}
Reflector	1×10^{14}	8×10^{13}	5×10^{13}	2×10^{13}

The requirements on the user to change from plate-type fuel to TRIGA fuel are minimal. The hardware modifications generally do not go beyond the requirement for new fuel handling and measurement tools and new control rods. The existing control rod drive mechanisms need not be changed (except in those cases where the user wishes to take advantage of the pulsing ability of the TRIGA fuel). In a few cases, it may be necessary to increase the coolant flow rate. In all cases, the appropriate analysis must be completed for safety review and license amendment as would also be the case in changing from an alloy to dispersion or other plate-type fuel form.

AVAILABILITY AND ECONOMY

As announced at the IAEA meeting on Research Reactor Renewal and Upgrading in Vienna in May, 1978, General Atomic is accepting orders for supply of high wt % fuels under standard terms and conditions including fuel warranty. The production capability for these fuels has been demonstrated at General Atomic and sufficient plant capacity is available for fuel production beyond existing orders. The time required to complete fuel fabrication would generally be less than the time required to obtain export licenses and/or operating license amendments as required.

In addition to the well-known and previously mentioned technical advantages of the TRIGA fuels, fuel cycle cost evaluations indicate the potential for significant savings. Burnup lifetime of TRIGA fuel ranges from about 2 to more than 5 times that of the plate-type fuel it replaces; however, the price differentials are significantly lower. In general the savings realized with the TRIGA fuel increase with reactor power level and duty factor. The core lifetimes given in Table 2 do not include the benefits which can be obtained by fuel shuffling or additions. The long core lifetimes give additional economic and operational advantages by reducing the fuel handling and shipping requirements, and by providing a stable core configuration giving consistent flux levels over a long period of time.

In short, the TRIGA fuel offers the advantages of:

- low enrichment available now
- reduced safeguards concerns
- easy export
- assured long-term supply
- inherent safety
- long-life stable core configuration
- significant fuel cycle cost savings

FUTURE DEVELOPMENT PLANS

The program for demonstration of the fuels up to 45 wt % is complete except for the high burnup test to be done in the ORR. It is anticipated that future work can be directed toward extending the technology for uranium contents to 60 wt % which would provide economically attractive fuel in a configuration suitable for power levels of 20 MW or more. More detailed analytical work will be carried out on a case-by-case basis for replacement of existing HEU TRIGA fuels as well as for potential plate-type reactor conversions.

DISCUSSION

TRAVELLI (ANL): One of my questions is about the high burnup. I was looking at your megawatt days for the reactors for which the fuel is developed and they range from 1200 to 7500 megawatt days. It seems to me that it is going to be a problem to achieve burnups as high as those which these fuels are meant to achieve. What tests are you considering about the high power burnup tests and what type of megawatt days?

GIETZEN: This high burnup test, demonstration test, as I mentioned, would be a standard 16 rod cluster configuration which we intend to put in the ORR. Recognize that the ORR is a 30 megawatt reactor and we will be testing fuel which is designed for power levels up to 15 megawatts. The burnups for the highest lifetimes mentioned are going to take roughly 20-24 months to achieve for the lower end of that list. The 1200 megawatt days for 2-3 MW reactors will perhaps be achieved within the first year. A question that is left open is what is the significance of that long term burnup test? Is that a safety consideration or is that strictly a commercial consideration to demonstrate that you can indeed achieve those lifetimes and therefore the economics that we predict? We believe it is only a commercial consideration.

SCHWARTZ (Saclay): Are the TRIGA fuel elements reprocessed?

GIETZEN: There is a reprocessing process which has been demonstrated at Idaho. It has been inactive since it was developed because the amount of TRIGA fuel which has been returned has been very low due to the long lifetime characteristics of the cores. There is at this time some backlog of fuel at Idaho and we anticipate that some time in the near future, meaning within the next few years, they will have to start up that process and do some reprocessing. But, the process has been demonstrated and is available.

BINFORD (ORNL): I noticed in your slide that in the 10 megawatt version of the TRIGA you had a thermal flux of 3×10^{14}. Now that's a 26 kilogram core at 10 megawatts and the average fissioning flux will be something like 2×10^{13}. Where is that 3×10^{14}?

GIETZEN: This is in a flux trap in the core.

TRAVELLI: You mentioned a 5% increase in loading that essentially is the only increase that is needed to take care of the reactivity loss due to the increasing ^{238}U when you go to low enrichment. Is that a 5% difference between the FLIP loaded core and the new core?

GIETZEN: No, that is the difference for the 45 wt % case which is the replacement for the fully enriched fuel in the 1/2 in. diameter configuration.

TRAVELLI: Do the two cores have a comparable lifetime?

GIETZEN: Yes, for the 1/2 in. diameter fuel, 45 wt % has a comparable lifetime to the fully enriched version it replaced. In the case of the FLIP replacement the ^{235}U loading in the replacement is lower than that in the original FLIP, which was 70% enriched.

TRAVELLI: The more ^{238}U you have, the less ^{235}U you have, or vice versa? I have your terminology a little confused.

GIETZEN: Let me try that again. In the 45 wt % case the ^{235}U content is slightly greater than that in the fully enriched version it replaces. And the reason for that slightly greater amount is to compensate for the ^{238}U poisoning. In the case of the FLIP fuel we are going to a lower ^{235}U content when we go from the 70% enriched to the 20% enriched since we are only going to 20 wt % uranium. There is no direct compensation required, the lifetime will be shorter, the reactivity will be kept the same by reducing the burnable poison content.

TRAVELLI: Is the lifetime of the 45% dense fuel longer or shorter than the FLIP fuel it replaces?

GIETZEN: The 45 wt % does not replace the FLIP, it replaces the fully enriched fuel and the lifetime is about the same. The FLIP replacement has a lower lifetime than the original FLIP. We believe it makes more sense because the amount of uranium required to match the original FLIP lifetime is excessive particularly now with the higher uranium price. It doesn't make sense to have such a large investment in uranium initially in the fuel element.

TRAVELLI: Is there a limit to the number of kilowatts per liter that the TRIGA fuel can handle?

GIETZEN: I don't know what that limit is. I know that to this point in time we have gone beyond the requirement for the 15 megawatt core with the 1/2 in. diameter rod. We have some preliminary analysis which shows that with smaller rod diameters and therefore increased heat transfer areas we can go to higher power densities. We simply haven't done that because we either haven't had the funding to do it or haven't had the customer who wanted us to do it for them.

BRUGGER (U. of Missouri): You mentioned that when you go to lower enrichment you will have to add more uranium to overcome the ^{238}U poisoning. Could I interpret that then that you will have more fast flux per thermal which is then an advantage for radiation damage but a disadvantage for neutron scattering experiments, for which your fast background is a real detriment.

GIETZEN: I think the differences there are really going to be pretty small. What you say is right, that effect is there but it is a small effect because the increase in ^{235}U loading over the fully enriched version that it replaced is very small. Whether that is an advantage or disadvantage from the experimental point of view depends on what you are doing. We know that it does give a higher fast to thermal ratio and still gives the same kind of thermal flux in the reflector or in a flux trap in the core.

SCHLAPPER (U. of Missouri): You specify an initial excess reactivity value of 8%. For your high power configuration, what is your excess reactivity level at the end of core life?

GIETZEN: I think they are around 4%. There is a certain amount of reactivity needed to override the negative temperature coefficient. John, what is your reactivity margin?

RANDALL (Texas A&M): This is something that's hard to get used to when going from a plate type where you hardly saw a megawatt. It takes us $2.60 to just get to one megawatt over our temperature coefficient. And that's at a power level of 1 megawatt.

I've got a comment. When I first saw your low enriched fuel for the FLIP conversion it struck me as a disadvantage because of the decrease in lifetime; we bought our fuel because of the long lifetime. However, it turns out as the political environment changes the lifetime is determined by politics, not the physical changes of the fuel. So I'm not sure that you don't have adequate lifetime in that fuel. In your testing I noticed you're putting in the 1/2 in. diameter pins in the ORR and, therefore, in the long term testing you're not doing the FLIP low enrichment conversion. When you did the testing as you're doing the testing in the MARK F, do you have some FLIP low enriched fuel in it?

GIETZEN: First, let me clarify for the first part of your question. We do intend to put 20 wt % into some of the 1/2 in. rods in the 16-rod configuration in the Oak Ridge test and we will do the appropriate adjustment in enrichment to get the proper operating fuel temperatures. So we will have that verification in the ORR test. In the present elements that are being operated in the MARK F there are both 20 wt % and 45 wt % elements operating.

RANDALL: I wouldn't trust that completely because when we went to the FLIP conversion for our reactor with a slightly larger fuel diameter many of the parameters predicted for us didn't work out. They were all overly optimistic. And so, I would worry about that kind of test.

GIETZEN: I understand that in this particular case it is not representative from two aspects: first, the geometry is different; secondly, it is a highly accelerated test and I think from that standpoint perhaps more extreme.

RANDALL: Well, having highly accelerated one or two of our fuel elements, I'm sensitive of that also. I'll talk to you later.

ALMENAS (U. of Maryland): I have a comment and a question. First, concerning the power density, for example, at 10 megawatts for a 30 cluster core, the power density comes out to be just averaged over the core close to 100 kilowatts per liter, which is right up there with the PWRs. Matter of fact, if you take the shroud away (it has a very massive shroud) it is somewhat above the average power density. This is certainly something that would have to be proved in the licensing stage because power densities of this nature for that large radius rod and at these low pressures have not been, well, at least licensed. That's a comment, now as far as the question; you mentioned certainly to go to higher power densities and you correctly say that you would have to decrease the radius of the rod and so on. This is, I guess, a philosophical type of question: how much do you decrease the radius of the rod and still have a TRIGA element? That is to say, we have been used to thinking of a TRIGA element as an element with an inherent negative temperature coefficient.