MASTER

IMPROVEMENT AND VERIFICATION OF
FAST REACTOR SAFETY ANALYSIS TECHNIQUES

Progress Report

James F. Jackson
T.F. Bott
and
Dee H. Barker

NOTICE
This report was prepared as an account of work sponsored by the United States Government. Neither the United States nor the United States Energy Research and Development Administration, nor any of their employees, nor any of their contractors, subcontractors, or their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness or usefulness of any information, apparatus, product or process disclosed, or represents that its use would not infringe privately owned rights.

Department of Chemical Engineering
Brigham Young University
Provo, Utah

June 1, 1976-September 30, 1976

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED ^{EB}

Prepared For The U.S. Energy
Research and Development Administration
Under Contract AT(11-1)-2571

427 attached

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency Thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.

ABSTRACT

VENUS-II calculations of the Kiwi-TNT, SNAPTRAN-2 and SNAPTRAN-3 experiments have been completed. These studies show good agreement between calculated and experimental fission energy release for all three experiments. Heat transfer effects were scoped in the Kiwi-TNT case and were shown to be readily capable of explaining the discrepancy noted between the experimental and calculated fission energy releases. Extensive sensitivity studies were conducted to demonstrate the relative insensitivity of the VENUS-II calculations to reasonable uncertainties in input parameters. ~~A summary paper presented at the Last Reactor Safety Topical Meeting of October 5-8, 1976, is appended to this report.~~

HEAT TRANSFER IN KIWI

The initial results of the VENUS-II comparison studies on the Kiwi-TNT excursion reported in the May annual progress report for this contract, showed the calculated fission energy to be high by about 50%. In order to improve the agreement between experiment and calculation two possible sources of error were investigated. The first concerned the heat capacity used in the calculation. The original study assumed all energy to be deposited in the graphite of the core, clearly a poor assumption. The heat capacity was modified to include a mass weighted average of fuel (UC_2) and graphite, thus assuming instantaneous heat transfer from fuel to graphite. This led to a result only 25% above the experimental value.

The second area of investigation concerned the effect of heat transfer from fuel bead to graphite moderator as discussed in our last progress report. This effect could be of great importance in the heat up and hence disassembly rate of the Kiwi-TNT core.

To estimate the possible effect of bead heat transfer on the Kiwi-TNT calculated results, a simple, implicit, two-node heat transfer calculation was checked out and implemented in the Venus II code.¹ In this calculation the Kiwi fuel beads were modeled as spheres of UC_2 completely enclosed by a shell of graphite with an adiabatic outer surface as shown in Figure 1. The UC_2 beads were known to be 75-150 μ in diameter. A nominal radius of 75 μ was chosen for the bead size and the beads were surrounded by graphite. The amount of graphite surrounding the bead was based on the average mass of graphite per unit mass of UC_2 as determined from Kiwi documents.² An error is introduced here since the bead loading varies throughout the Kiwi core. Also

ignored was the thermal resistance of the pyrocarbon coating on the fuel beads and the contact resistance of the bead to graphite interface.

The fission rate in the beads of UC_2 was estimated to be 25 times the average fission rate for the whole core.² Not all the fission energy was considered as deposited in the fuel beads, however. Of the 185 MEV/fission energy deposition assumed in this study all prompt γ and fission neutron heating, about 17 MEV/fission, was assumed to occur in the graphite. In addition, based on a fission product stopping distance of 10μ ,³ about 4% of the fission product energy was assumed deposited outside the fuel bead. This led to a energy deposition rate in the fuel bead that was 22.1 times the average for the whole reactor. This factor was used to modify the normal, uniform energy source used in each mesh cell in the Venus-II code, and served as a heat source for the fuel material. The remainder of the fission energy was deposited in the graphite and served as a heat source for this material.

The temperature reactivity feedback coefficient given in the Kiwi literature was apparently due to expansion of the core, so the graphite temperature was used to calculate this feedback.⁴ The graphite temperature was also used to calculate a temperature dependant graphite heat capacity and a graphite vapor pressure.⁵ The fuel temperature was used to calculate a UC_2 vapor pressure based on an expression from Liebowitz.⁶ The remainder of the Venus-II model was used in the conventional manner.

The results of the heat transfer calculations showed that, using nominal values for all pertinent parameters, the energy release was 1.4×10^4 Mw-sec which is lower than the lower limit on the ex-

perimental energy release by a factor of five. The results of the calculations are functions of the heat transfer, UC_2 vapor pressure and Kiwi neutronics parameters. Varying these parameters within their experimental error band could raise the energy release to 1.8×10^4 Mw-sec, or about one fourth the experimental value while peak power was below and occurred before the experimental value (see Figure 2). Sensitivity studies on the heat transfer model showed that the most sensitive parameters in controlling energy release were the heat capacity of the UC_2 and the fuel bead to volumetric power generation density. Doubling the UC_2 heat capacity nearly doubled the energy release, as did halving the fuel bead to power density.

These studies indicate that heat transfer is an important effect in the Kiwi-TNT excursion and could easily account for the discrepancy between the nominal Venus II calculation and the actual experimental results.

SNAPTRAN-2 Experiment

The SNAPTRAN-2 reactor was basically a SNAP 2/10A-type core and reflector, with special control-drum assemblies designed to provide an extremely rapid reactivity insertion. Some of the core properties important in a VENUS calculation are summarized in Table II.

The system reactivity is controlled through rotation of the beryllium control drums. The core is very small, being only about 9 inches in diameter and about 12 inches high. It is fueled with fully enriched uranium in zirconium-hydride. The disassembly excursion was initiated by the rapid insertion of \$4.94 of reactivity.

The only modifications of VENUS-II required to analyze this excursion was the addition of an equation-of-state appropriate to the U-ZrH₂ fuel material. The equation-of-state used for the SNAPTRAN-2 reactor is very similar to that used in the Kiwi-TNT model. The U-ZrH₂ vapor pressure was represented by⁷

$$P(T) = 9.847 \times 10^{14} \exp(-19317/T)$$

where

$$P(T) = \text{vapor pressure in dynes/cm}^2$$

$$T = \text{temperature in } ^\circ\text{K}.$$

The temperature of the reactor material was calculated in the same manner as in the Kiwi model except for the specific heat of the core material. The heat capacity used was:⁸

$$C_p(T) = 0.376 + 2.25 \times 10^{-4}T + 4.133 \times 10^{-8} T^2 \text{ (J/gm)}.$$

A treatment of the H_x dissociation energy is included in the SNAPTRAN model. This accounts for the energy required to remove hydrogen from the U-ZrH₂ fuel. The vapor pressure is principally due to H₂ molecules released when the U-ZrH₂ is heated. The H₂ is then treated like an ideal gas, and the amount of H₂ generated in a given time step is calculated using the pressure change in that time step. The heat of release for the U-ZrH₂ is 12,000 J/gm⁴ of hydrogen released. Provision is made using corresponding states and assuming single-phase pressures in SNAPTRAN-2 with a bulk expansion expression for ZrH₂ of:⁹

$$(T) = {}_0(1 - 1.55 \times 10^{-4} T).$$

The initial conditions and physics parameters SNAPTRAN-2 are given in SNAPTRAN documents.⁸ Material worth distributions were derived from an importance function based on the square of the power distribution. The total reactivity worth of the core materials was taken from SNAPTRAN

sources,¹⁰ and was found to be about \$19 or .153 in fractional reactivity.

Results

The item of principal interest in the SNAPTRAN-2 and SNAPTRAN-3 calculations is the energy release. This result is summarized and compared with the experimental result in Table III. Also of interest is the relative time scale of events in the calculated and actual cases. Figure 3 compares the power trace as calculated by the VENUS-II code and the experimental power trace. The experimental power trace was plotted relative to an arbitrary time scale. Thus, to compare the calculated and experimental power traces, a particular point in time on the experimental trace was matched with a point in time on the VENUS power trace where the power and period were equal. Figure 4 shows that the shape and time scale of the calculated and experimental power traces are virtually identical.

Because of uncertainties in the temperature feedback for SNAPTRAN, two different cases have been run corresponding to different limiting values of the feedback coefficient given in SNAPTRAN documentation. The calculated and experimental results for these sensitivity cases are shown in Table IV.

The effect of variations in the temperature feedback reactivity coefficient on the energy release and peak power. The effect on the peak power is more pronounced since the reactivity is a primary parameter in determining peak power. The effect of peak power is a secondary effect on energy release since energy release is an integrated function of power. The effect of reactivity feedback variation on peak temperature is small.

The effect of the equation of state variations was also studied. The U-ZrH₂ equation of state is considered the most reliable but a Zr-H₂ model was also used for comparison. Using the Zr-H₂ vapor pressure expression an energy release of 67.2 MW-sec is obtained while for the U-ZrH₂ a value of about 48 MW-sec is calculated. For the peak power, a range of 5.9-7.3 x 10⁴ MW-sec is obtained experimentally while the Zr-H₂ case gives 9.0 x 10⁴ MW-sec and the U-ZrH₂ case gives 6.7 x 10⁴ MW-sec. These results are summarized in Table V and show the relative insensitivity of the VENUS-II calculation to variations in equation of state.

A further sensitivity study was conducted by varying the magnitude of the total reactivity worth of the core materials. To test the effect of the uncertainty in the total worth on the energy release and peak power, the material worth was increased by 50% and by 200%. At a total worth of .153, the peak power is 6.7 x 10⁴ MW and the energy release is 49 MW-sec using a U-ZrH₂ EOS. With a total worth of .5 the values are 6.5 x 10⁴ MW and 40.3 MW-sec with the U-ZrH₂ EOS. This result is reassuring since it shows that a factor of 3 variation in the value of the total material worth has a small effect on the final result. This is due to the fact, observed both experimentally and in the VENUS calculations, that the peak power is determined by the temperature coefficient in the SNAPTRAN-2 test. Core disassembly occurs after peak power and serves principally to "pinch off" the energy release for the excursion.

SNAPTRAN-3

The SNAPTRAN-3 destructive test used a SNAPTRAN-2/10A core, without its beryllium reflector, surrounded by a Binal sleeve. This Binal sleeve held the reactor sub-critical. The entire assembly was placed in a large environmental water tank designed to simulate a large body of water. The binal sleeve was then rapidly removed resulting in the insertion of $\$3.75 + .25$ of excess reactivity. This led to an energetic excursion and disassembly of the core.

For a VENUS-II calculation the SNAPTRAN-3 core was modeled almost exactly like the SNAPTRAN-2 core. One major difference between the two was the power shape. Because of the water surrounding the SNAPTRAN-3 core, this core showed considerable power peaking at the core edge that was not present in SNAPTRAN-2. Also, the fast neutron lifetime in the SNAPTRAN-3 core was about twice that in the SNAPTRAN-2 core. The beryllium moderator on the SNAPTRAN-2 core was changed to a 140 cm water reflector to run the SNAPTRAN-3 case. The temperature coefficient of reactivity was slightly smaller in the SNAPTRAN-3 case, being $2.734 \times 10^{-5}/^{\circ}\text{C}$.¹¹ The U-ZrH₂ EOS and the SNAPTRAN-2 heat capacity were used. The remainder of the VENUS-II code was used without modification.

Results

The results of the VENUS-II calculation on SNAPTRAN-3 were very close to the experimental results. The experimental energy release was 32.7 - 61.3 MW-sec with a most probable value of 45. + 4 MW-sec. The calculated result was 33.7 MW-sec with nominal parameters. Sensitivity studies showed that varying the initial reactivity to the top or bottom

of its error band raised or lowered the energy release to 35.9 and 30.0 MW-sec respectively. Temperature feedback effects were similar to those in SNAPTRAN-2 as were displacement feedback effects.

The peak power for the SNAPTRAN-3 test was experimentally determined to be $16 - 22 \times 10^3$ MW at a relative time of 6 milliseconds. The VENUS results indicate peak power of 18.2×10^3 MW at a time of 5.8 milliseconds on the same scale.

The peak temperature indicated by experimental data was above 1255 °K. The maximum VENUS calculated temperature was about 1350°K. The pressure in the core was calculated to be about 15,000 psi at disassembly. No experimental pressure data was given.

The core boundary motion was well documented in the SNAPTRAN-3 test and was compared to the calculated results. This comparison shows good qualitative agreement in shape between the calculated and photographed core boundaries. Quantitatively, the VENUS-II displacement calculations seem to be ahead of the photographic results. As an example, at .95 milliseconds after peak power, the VENUS-II maximum radial boundary displacement is about 2.4 inches. For the photographic data, a comparable point is not reached until about 1.8 milliseconds after peak power. This apparent shift may be either due to a shift or error in the reported peak power (only accurate to about + 1 millisecond) or may be an actual discrepancy. The velocity of the radial boundary is in good agreement. At a displacement of about two inches the experimental velocity is about 4000 in/sec while the calculated velocity is about 7000 in/sec. The outer core boundary motion began in the calculation at about .4 milliseconds after peak power. In the experiment, boundary motion became noticeable at about .6 milliseconds

after peak power.

The most important effect of disassembly, interior core motion in the high worth region of the core, could not be related to channel closure data because of the lack of a common datum or reference point. To verify a proper handling of interior core motion one must either rely on indirect verification through the energy release and power trace, or an experiment with pin displacement measurements in the core interior must be sought.

Summary of Sensitivity Studies

To verify that the selection of parameter values involved in the calculations had not led to fortuitous agreement, sensitivity studies were performed by varying key parameters within their estimated experimental uncertainties. The parameters considered included the temperature feedback reactivity coefficient, material motion reactivity worths, heat capacity, fuel vapor pressure and initial reactivity insertion. These studies revealed no parameter uncertainties that would significantly alter the results of the base case for the SNAPTRAN tests.

Sensitivity cases involving the variations of several key parameters within their estimated uncertainty limits were also run for Kiwi-TNT to show the stability of these results with respect to parameter uncertainties. The parameters considered included temperature feedback reactivity coefficient, material motion reactivity worths, heat capacity, fuel vapor pressure, and initial reactivity insertion. These studies indicate that only the fuel heat capacity and heat transfer effects had a strong influence on the total energy release. Results

of these sensitivity studies are summarized in Table VIII.

Summary

As an overall summary and assessment of the comparison studies completed, the following paper presented at the American Nuclear Society's Fast Reactor Safety Topical Meeting is appended.

Publications

T.F. Bott and J.F. Jackson, "Experimental Comparison Studies with the VENUS-II Disassembly Code," was presented at the American Nuclear Society Fast Reactor Safety Topical Meeting in Chicago, (Oct. 1976).

Note: This paper is attached as a summary of the work done in this period.

Removed

References

1. J.F. Jackson and R.B. Niholson, "VENUS-II: An LMFBF Disassembly Program," ANL-7951 (1972).
2. L.D.P. King, Safety Neutronics for Rover Reactors, LA-3358-MS, 1965.
3. J.R. LaMarsh, Nuclear Reactor Theory, Addison-Wesley Publishing Co., 1966.
4. "Primary Radiological Safety Guide and Safety Analysis for Kiwi-B Reactors," LAMS-2710 (1964).
5. C.L. Mantell, Carbon and Graphite Handbook, Interscience Publishers (1968).
6. L. Leibowitz, Arsonne National Laboratory, Private communication.
7. W.T. Foreman and M. Shuler, Jr., Measurements of U Zr H₂ Properties in an Intense Neutron Flux, Edgerton, Germes-Hansen & Greer, Inc., Number B-3101, 15 Sept. 1965.
8. J.F. Jackson, W.F. Rhoades, and L.I. Moss, "Analysis of SNAPTRAN-1 and -2 Reactor Kinetics Experiments," NAA-SR-11850 (1967).
9. W.R. Stratton, et al., "Reactor Power Excursion Studies, LASL Progress Report, 1971.
10. W.R. Castle, "Snaptran Core Reactivities," NAA-SR-MEMO-9453, January 23, 1964.
11. W.E. Kessler, et al. SNAPTRAN 2/10A-3 Destructive Test Results, 1D0-17019, Phillips Petroleum Co., Atomic Energy Division, (January, 1965).

TABLE I

Comparison of Energy Releases for KIWI-TNT
"Base Case" and Bead Heat Transfer Case

	Experimental Energy Release (Mw-sec)	Calculated Energy Release (Mw-sec)
KIWI-TNT Base Case	8090 - 9889	12350
KIWI-TNT with Bead Heat Transfer Model	8090 - 9889	1400.0

TABLE II
Key Parameters and Initial Conditions
for SNAPTRAN and KIWI-TNT Tests

Parameter	SNAPTRAN-2	SNAPTRAN-3	KIWI-TNT
Delayed Neutron Fract Fraction, β	$80. \times 10^{-4}$	$80. \times 10^{-4}$	$74. \times 10^{-4}$
Prompt Neutron Life-time Λ (μ -sec)	6.5	14	33.8
Temperature Reactivity Feedback Coeff. ($^{\circ}\text{K}^{-1}$)	-3.36×10^{-5}	-2.93×10^{-5}	-1.32×10^{-5}
Initial Temperature ($^{\circ}\text{K}$)	293.0	293.0	293.0
Initial Power (watts)	0.01	0.01	2.25×10^6
Initial Reactivity Insertion ($\$$)	4.91	3.60	8.30
Core Void Fraction (%)	11	1	26.8
Total Material Reactivity Worth	.153	.153	.504
Core Mass (Kg)	5.09 of U 45.85 of ZrH_2	5.09 of U 45.85 of ZrH_2	189.4 of UC_2 1012.8 of C

TABLE III

Comparison of Calculated and Experimental Energy
Releases for SNAPTRAN and KIWI-TNT Tests

	Experimental	Calculated
	Energy Release (Mw-sec)	Energy Release (Mw-sec)
SNAPTRAN-2	38.0 - 47.3	47.0
SNAPTRAN-3	32.7 - 61.3	33.7
KIWI-TNT	8090.0 - 9889.0	12350.0

TABLE IV
EFFECT OF TEMPERATURE COEFFICIENT ON
SNAPTRAN-2 RESULTS

Parameter	VENUS II $-3. \times 10^{-5}/^{\circ}\text{K}^*$	VENUS-II $-3.36 \times 10^{-5}/^{\circ}\text{K}^*$	Experiment	Reference
Peak Power	$7.4 \times 10^{10}\text{w}$	$6.7 \times 10^{10}\text{w}$	$5.9-7.3 \times 10^4\text{mw}$	10
Energy Release	$4.8 \times 10^7\text{j}$	$4.7 \times 10^7\text{j}$	3.8-47. mw-sec	4
Minimum Period	$2.17 \times 10^{-4}\text{sec}$	$2.17 \times 10^{-4}\text{sec}$	$2.06 \times 10^{-4}\text{sec}$	10
Time of Peak Power	6.656 ms	6.66 mx	$6.4 \pm 2 \text{ ms}$	10
Peak Temperature due to Nuclear Heating	1590 °K	1550 °K	Not Available	--

* temperature coefficient being used

TABLE V
COMPARISON OF VENUS-II CALCULATIONS FOR SNAPTRAN-2
USING DIFFERENT VAPOR PRESSURE EXPRESSIONS

Parameter	VENUS-II ZrH ₂	VENUS-II U -ZrH ₂	Experiment	Reference
Peak Power	9×10^4 MW	6.7×10^4 mw	$5.9-7.3 \times 10^4$ mw	10
Energy Release	67.2 mw-sec	48 mw-sec	3.8-47. mw-sec	4
Time of Peak Power	6.81 ms	6.76 ms	6.4 ± 2 ms	10
Peak Temperature Due to Nuclear Heating	2470°K	1560°K	Not Available	--

TABLE VI
COMPARISON OF VENUS-II CALCULATIONS FOR SNAPTRAN-2
USING DIFFERENT TOTAL WORTHS

Parameter	VENUS-II .153 Total Worth	VENUS-II .570 Total Worth	Experiment	Reference
Peak Power	$6.7 \times 10^4 \text{ mw}$	$6.5 \times 10^4 \text{ mw}$	$5.9-7.3 \times 10^4 \text{ mw}$	10
Energy Release	48 mw-sec	40.3 mw-sec	3.8-47. mw-sec	4
Time of Peak Power	6.76 ms	6.65 ms	$6.4 \pm 2 \text{ ms}$	10
Peak Temperature Due to Nuclear Heating	1560°K	1420°K	Not Available	--

TABLE VII

COMPARISON OF EXPERIMENTAL RESULTS AND
VENUS-II CALCULATION FOR SNAPTRAN-3

Parameter	Nominal Venus-II Case	Experimental Result
Peak Power	18,200 mw	18000-22000 Mw
Energy Release	33.7 MW-sec	32.7-61.3 Mw-sec
Time of Peak Power	5.8 Msec	6 $\pm$.3 msec
Minimum Period	664 Msec	.630-.780 Msec
Peak Temperature	1350°K	> 1255°K
Pressure at Onset of Disassembly	11700 psi	~15000 psi

TABLE VIII

SENSITIVITY OF VENUS-II CALCULATIONS
OF KIWI-TNT EXCURSION TO
VARIOUS PARAMETER UNCERTAINTIES.

Parameter	Variation	Effect on Peak Power	Effect on Energy Release
Temperature Feed-back Coefficient	+20%	-19%	-7%
	-20%	+25%	+10%
Total Material Reactivity Worth	+15%	- <1%	- <1%
	-15% *	+1%	+1%
Heat Capacity	+50%	+50%	+43%
	-50%	-50%	-47%
Vapor Pressure	$P \times 10^1$	-1%	-7%
	$P \times 10^{-1} *$	+15%	+17%
Initial Reactivity	+30¢	+10%	+1%
	-30¢ *	-5%	- <1%

* Denotes sensitivity run on Heat Transfer Case.

Figure 1. Kiwi Fuel-Bead Model Geometry

Figure 2. Comparison of Experimental and Calculated Power Traces for Kiwi-TNT.

Figure 3. Comparison of SNAPTRAN-2 Experimental and Calculated Power Traces.

Figure 4. Comparison of SNAPTRAN-3 Experimental and Calculated Power Traces.