

2

**CODE DEVELOPMENT AND ANALYSIS PROGRAM**

**FUEL THERMAL CONDUCTIVITY (FTHCON)**

D. L. HAGRMAN

February 1979

 **EG&G** Idaho, Inc.



IDAHO NATIONAL ENGINEERING LABORATORY

**DEPARTMENT OF ENERGY**

IDAHO OPERATIONS OFFICE UNDER CONTRACT EY-76-C-07-1570

**MASTER**

## 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.**

#### **NOTICE**

This report was prepared as an account of work sponsored by the United States Government. Neither the United States nor the Department of Energy, nor the Nuclear Regulatory Commission, 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.



FORM EG&G-398  
rev. 12-78)

## INTERIM REPORT

Accession No. \_\_\_\_\_

Report No. CDAP-TR-049

**Contract Program or Project Title:** Material Property Analysis

**Subject of this Document:** Fuel Thermal Conductivity (FTHCON)

**Type of Document:** Status Report

**Author(s):** D. L. Hagrman

**Date of Document:** February 1979

**Responsible NRC Individual and NRC Office or Division:** G. P. Marino, Reactor Safety Research

This document was prepared primarily for preliminary or internal use. It has not received full review and approval. Since there may be substantive changes, this document should not be considered final.

EG&G Idaho, Inc.  
Idaho Falls, Idaho 83401

Prepared for the  
U.S. Nuclear Regulatory Commission  
and the U.S. Department of Energy  
Idaho Operations Office  
Under contract No. EY-76-C-07-1570  
NRC FIN No.

#### NOTICE

This report was prepared as an account of work sponsored by the United States Government. Neither the United States nor the United States Department of Energy, 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.

## INTERIM REPORT

**DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED**

CONTENTS

5.4 S  
5.3 S  
5.0 S

NOV 1966  
DEF INR  
SAIGM

COMBUSTION  
MATERIALS

THEORY AND AVAILABLE DATA . . . . . 1

L CONDUCTIVITY . . . . . 2

COND. CONDIT. . . . . 2

literature: Theory and Available Data. . . . . 5

ment. . . . . 23

the Model . . . . . 27

Activity Subcode FTHCON Listing and  
PRO-11 Version of the Subcode . . . . . 36

. . . . . 42

FIGURES

A-2.1	Model prediction for thermal conductivity of 0.99 of theoretical density $UO_2$ compared to data from specimens with densities in the range 0.985 to 0.995 of theoretical density . . . . .	28
A-2.2	Model prediction for thermal conductivity of 0.98 of theoretical density $UO_2$ compared to data from specimens with densities in the range of 0.975 to 0.985 of theoretical density. . . . .	29
A-2.3	Model prediction for thermal conductivity of 0.96 of theoretical density $UO_2$ compared to data from specimens with densities in the range 0.955 to 0.965 of theoretical density . . . . .	30
A-2.4	Model prediction for thermal conductivity of 0.95 of theoretical density $UO_2$ compared to data from specimens with densities in the range 0.945 to 0.955 of theoretical density . . . . .	31
A-2.5	Model prediction for thermal conductivity of 0.94 of theoretical density $UO_2$ compared to data from specimens with densities in the range 0.935 to 0.945 of theoretical density . . . . .	32
A-2.6	Model prediction for thermal conductivity of 0.93 of theoretical density $UO_2$ compared to data from specimens with densities in the range 0.925 to 0.935 of theoretical density . . . . .	33
A-2.7	Model prediction for thermal conductivity of 0.91 of theoretical density $UO_2$ compared to data from specimens with densities in the range 0.905 to 0.915 of theoretical density . . . . .	34
A-2.8	Model prediction for thermal conductivity of 0.89 of theoretical density $UO_2$ compared to data from specimens with densities in the range 0.895 to 0.905 of theoretical density . . . . .	35
A-2.9	Comparison of thermal conductivity predicted by the MATPRO-11 version of FTHCON to the conductivity returned by the current subcode for 0.95 of theoretical density $UO_2$ . . . . .	40
A-2.10	Comparison of thermal conductivity predicted by the MATPRO-11 version of FTHCON to the conductivity returned by the current subcode for 0.90 of theoretical density $UO_2$ . . . . .	41

TABLES

A-2.I	UO <sub>2</sub> data from Christensen. . . . .	12
A-2.II	UO <sub>2</sub> data from Godfrey et al. . . . .	13
A-2.III	UO <sub>2</sub> data from Bates' thermal diffusivity measurements. . .	15
A-2.IV	UO <sub>2</sub> data from Gibby's thermal diffusivity measurements. . . . .	18
A-2.V	UO <sub>2</sub> data from Weilbacher's thermal diffusivity measurements. . . . .	19
A-2.VI	UO <sub>2</sub> data from Goldsmith and Douglas' thermal diffusivity measurements . . . . .	21
A-2.VII	UO <sub>2</sub> data from Hobson et al.'s thermal diffusivity measurements . . . . .	22
A-2.VIII	Values of $\beta_0$ and $\beta_1$ from various density groups. . . . .	24
A-2.IX	Listing of the FTHCON. . . . .	37

## FORWARD

This report describes an improvement of the fuel thermal conductivity subcode which is part of the fuel rod behavior modeling task performed at EG&G Idaho, Inc. The original version was published in the Materials Properties (MATPRO) Handbook<sup>[a]</sup> Section A-2 (Fuel Thermal Conductivity).

The improved version incorporates data which were not included in the previous work and omits some previously used data which are believed to come from cracked specimens. The models for the effect of porosity on thermal conductivity and for the electronic contribution to thermal conductivity have been completely revised in order to place these models on a more mechanistic basis. As a result of modeling improvements the standard error of the model with respect to its data base has been significantly reduced.

The material property correlations and computer subcodes described in MATPRO are developed for Use in Light Water Reactor (LWR) analytical programs such as the FRAPCON-1<sup>[b]</sup> and FRAP-T4<sup>[c]</sup> codes. This work is being performed as part of the broad effort to develop and verify analytical models capable of describing nuclear fuel rod behavior.

The format and numbering scheme used in this report is consistent with its intended use as a replacement for the second section of Appendix A of the MATPRO handbook. It is beyond the scope of this report to provide a complete description of the MATPRO subcode and its organization. Readers who require descriptions of the use of materials properties subcodes should consult the code descriptions<sup>[b,c]</sup>.

---

[a] D. L. Hagerman and G. A. Reymann (Eds), MATPRO Version 11 - A Handbook of Materials Properties for use in the Analysis of Light Water Reactor Fuel Rod Behavior, TREE-1280, NUREG-CR-0497, (to be published, February 1979).

[b] G. A. Berna et al, FRAPCON-1: A Code for the Steady-State Analysis of Oxide Fuel Rods, CDAP-TR-78-032-R1, (November 1978).

[c] J. A. Dearien et al, FRAP-T4: A Computer Code for Transient Analysis of Oxide Fuel Rods - Volume 1 - Analytical Models and Input Manual, CDAP-TR-78-027, (July 1978).

## 2. FUEL THERMAL CONDUCTIVITY (FTHCON)

(D. L. Hagrman)

In this section a correlation is presented for the thermal conductivity of uncracked  $UO_2$  and  $(U,Pu)O_2$  fuels. This property and the closely associated models for the effect of fuel cracking on temperature distributions within the fuel are critical to accurate predictions of fuel rod behavior in both steady state operation and in off-normal transients because fuel rod behavior is critically dependent on temperature.

### 2.1 Summary

The FTHCON subcode determines the fuel thermal conductivity and its derivative with respect to temperature as a function of temperature, density, oxygen to metal ratio and the plutonium content of the fuel. Burnup is also a required input but it is used only to calculate the melt temperature.

The model presented here is similar to the correlations used in MATPRO-5 to MATPRO-11 but predicts a somewhat higher conductivity than earlier versions because some data which were apparently taken with cracked specimens are no longer used. Also, the expression for the effect of porosity has been revised to consider more data than the expression used in previous versions of MATPRO. The current data base shows no significant effect of porosity at temperatures above about 1600 K, probably because of the effects of radiation and gas conductivity which increase pore conductivity at high temperature. Although no data for the conductivity of molten fuel have been found, physical considerations have led to a revised estimate for the thermal conductivity of liquid fuel. The new estimate for the thermal conductivity of molten fuel is about half as large as earlier estimates. Finally, a discontinuity in the slope of the MATPRO-5 to MATPRO-11 correlations for thermal conductivity as a function of temperature has been removed.

With the exception of minor modifications made to eliminate discontinuities in slope in the temperature range 1364 to 2300 K the expression used to model thermal conductivity of solid fuel is

$$k = \left[ \frac{D}{1 + (6.5 - 0.00469T')(1-D)} \right] \left[ \frac{C_v}{(A+BT^n)(1+3e_{th})} \right] + 5.2997 \cdot 10^{-3} T \left[ \exp\left(\frac{-13358}{T}\right) \right] \left[ 1 + 0.169 \left[ \frac{13358}{T} + 2 \right] \right]^2 \quad (\text{A-2.1})$$

where

- $k$  = thermal conductivity (W/(mK))
- $D$  = fraction of theoretical density (unitless)
- $C_v$  = phonon contribution to the specific heat at constant volume (J/(kgK)). The first term of the MATPRO correlation for fuel specific heat capacity is used for this factor<sup>[a]</sup>.
- $e_{th}$  = linear strain caused by thermal expansion when temperature is above 300K (unitless). The MATPRO correlation for fuel thermal expansion is used for this factor.
- $T$  = fuel temperature (K)

[a] The analytical expression for  $C_v$  as a function of temperature,  $T$ , and plutonium content, comp, is

$$C_v = \frac{296.7 (535.285)^2}{T^2 \left( \exp\left(\frac{535.285}{T}\right) - 1 \right)^2} \left[ \exp\left(\frac{535.285}{T}\right) \right] \left[ (1-\text{comp}) \right] + \frac{237.4 (571)^2}{T^2 \left( \exp\left(\frac{571}{T}\right) - 1 \right)^2} \left[ \exp\left(\frac{571}{T}\right) \right] \text{comp} \quad (\text{A-2.1a})$$

- T' = fuel temperature if the temperature is less than 1364K. For temperatures above 1834K the porosity factor,  $\frac{D}{1 + (6.5 - 0.00469T')(1-D)}$ , is equal to 1 and for temperatures in the range 1364-1834K the factor is interpolated as explained in Section 2.3.
- T'' = fuel temperature if the temperature is less than 1800K. For temperatures above 2300K, T'' is equal to 2050 K and for temperatures in the range 1800-2300K, T'' is interpolated as explained in Section 2.3.
- A = a factor which is proportional to the point defect contribution to the phonon mean free path (ms/kg). The correlation used for this factor is  $0.339 + 11.1 * \text{Absolute value (2.0-oxygen to metal ratio)}$ .
- B = a factor which is proportional to the phonon-phonon scattering contribution to the phonon mean free path (ms/kgK). The correlation used for this factor is  $0.06867 + (1 + 0.6238 * \text{plutonium content of fuel})$ .

The first term of Equation (A-2.1) represents the phonon contribution to specific heat and the second term represents the electronic (electron-hole) contribution. When the fuel is molten, the first term is neglected.

The expected error of the thermal conductivity model has been estimated by computing the standard error of the model with respect to its data base. For stoichiometric  $UO_2$  samples the standard error was 0.2W/(mk) and for stoichiometric mixed oxide samples with  $PuO_2$  the standard error was 0.3W/(mk). Based on these results, the following expression is used to calculate the expected standard error of the solid fuel thermal conductivity

$$U_k = (0.2 (1-COMP) + 0.7 COMP) * (1.0 + |2-OTM|10) \quad (A-2.2)$$

where

Uk = expected standard error of solid fuel thermal conductivity (W/(mK))

COMP = PuO<sub>2</sub> content of the fuel (ratio of weight of PuO<sub>2</sub> to total weight)

OTM = oxygen to metal ratio of fuel (unitless)

The following subsection is a review of the general theories and data used to derive the model for fuel thermal conductivity. Section 2.3 describes the development of the model and Section 2.4 is a discussion of the model's uncertainty. A code listing and comparisons to earlier versions of the code is presented in Section 2.5. Section 2.6 contains references.

## 2.2 Review of Literature: Theory and Available Data

The mechanistic basis for a description of the thermal conductivity of solid unirradiated UO<sub>2</sub> and (U,Pu)O<sub>2+x</sub> is well documented in the literature [A-2.1,A-2.4]. The thermal conductivity is the sum of contributions due to lattice vibrations, electron-hole pairs and infra-red radiation heat transfer. At temperatures below 1500 K the lattice component

$$K_p = 1/3 \rho C_v u \lambda \quad (A-2.3)$$

where

K<sub>p</sub> = lattice vibration (phonon) contribution to thermal conductivity (W/(mK))

ρ = density of the solid (Kg/m<sup>3</sup>)

C<sub>v</sub> = phonon contribution to the specific heat at constant volume (J/KgK)

u = mean phonon speed (m/s)

$\lambda$  = phonon mean free path (m)

is the most important contribution. At temperatures above 2000 K there is sufficient thermal energy to create significant numbers of electron-hole pairs. These pairs contribute

$$K_e = 2 \left[ \frac{k_B}{e} \right]^2 T \left[ \sigma + \frac{2\sigma_e \sigma_h}{\sigma} \left( \frac{E_g}{2k_B T} + 2 \right)^2 \right] \quad (\text{A-2.4})$$

where

$K_e$  = electronic contribution to thermal conductivity

$k_B$  = Boltzman's constant,  $1.38 \times 10^{-23}$  J/K

e = electron charge,  $1.6 \times 10^{-19}$  coulombs

$\sigma_e$  = electron contribution to electrical conductivity (1/ohm m)

$\sigma_h$  = hole contribution to electrical conductivity (1/(ohm m))

$\sigma$  =  $\sigma_e + \sigma_h$  (1/(ohm m))

$E_g$  = energy gap between conduction and valence bands (J)

T = temperature (K)

to the thermal conductivity<sup>[A-2.4]</sup> if the solid is not doped with donors or acceptors<sup>[a]</sup>. The radiation heat transfer contribution to the thermal conductivity is small in polycrystalline fuel<sup>[A-2.1]</sup>, presumably because the material is transparent only at long wavelengths.

---

[a] Equation (A-2.4) models both the kinetic transport of thermal energy and the bipolar heat-conduction effect caused by the creation of electron-hole pairs at high temperature and their recombination at low temperatures. The bipolar effect is not present in heavily doped semiconductors.

The application of Equation (A-2.4) is simplified by the existence of accurate measurements of the electrical conductivity of  $UO_2$ . Bates, Hinman and Kawada<sup>[A-2.5]</sup> report electrical conductivities above 1400 K to be given by

$$\sigma = 3.569 \cdot 10^7 \exp \left( - \frac{E_g}{2K_B T} \right) \quad (A-2.5)$$

where

$\sigma$  = electrical conductivity (1/(ohm·m)).

$K_B$  = Boltzman's constant,  $1.38 \cdot 10^{-23}$  J/K

$E_g$  = energy gap between conduction and valence bands,  $3.688 \cdot 10^{-19}$  J

$T$  = temperature (K)

Equation (A-2.4) can be combined with Equation (A-2.5) to obtain

$$K_e = 2 \left[ \frac{K_B}{e} \right]^2 * T * 3.569 \cdot 10^7 \left[ \exp \left( \frac{-E_g}{2K_B T} \right) \right] \left[ 1 + \frac{2f}{(1+f)^2} \left( \frac{E_g}{2K_B T} + 2 \right)^2 \right] \quad (A-2.6)$$

where  $f = \sigma_h / \sigma_e$  and the other symbols have been defined in conjunction with the two previous equations. Equation (A-2.6) contains only one undetermined parameter, the ratio  $f$ .

Unfortunately, the application of Equation (A-2.3) for the lattice contribution to thermal conductivity is complex.  $C_v$  and  $\rho$  are available from the MATPRO routines for fuel specific heat and fuel thermal expansion and  $u$  is approximately the speed of sound in the lattice but the phonon mean free path,  $\lambda$ , is not a directly measured quantity. For the purpose of applying Equation (A-2.3) to  $(U,Pu)O_2$  it is sufficient to point out that the quantity  $1/3u\lambda$  in Equation (A-2.3) at temperatures in the range 500-3000K is determined by two main contributions -- the deflection or scattering of lattice vibrations from permanent defects in the regular

lattice pattern and the scattering of lattice vibrations from each other<sup>[a]</sup>. The first contribution is primarily a function of the oxygen-to-metal ratio and the impurity content of the fuel while the second contribution is a function of temperature and the plutonium content of the fuel<sup>[A-2.1]</sup>. When the two main contributions to the phonon mean free path are incorporated in Equation (A-2.3) the appropriate expression for the lattice vibration contribution to the thermal conductivity of solid fuel is

$$K_p = \frac{\rho C_v}{A + BT} \quad (A-2.7)$$

where A is a function of the number of permanent defects in the lattice and B is a measure of the probability that lattice vibrations interfere with each other. The second term in the denominator is proportional to temperature because the density of lattice vibrations is proportional to temperature in the range 500-3000 K.

For porous material, some modification of Equation (A-2.7) is required because the pores do not have the same conductivity as the lattice. The physical problem has been discussed extensively in the literature<sup>[A-2.1, A-2.6 to A-2.10]</sup> where it has been shown that the effect of porosity is not only a function of the porosity fraction (volume of pores/total volume) but also dependent on pore shape, the thermal conductivity of any gas trapped within the pores and the emissivity of the lattice.

Unfortunately, the detailed mechanistic analysis presented in the literature cannot be applied to most of the published thermal conductivity data because the pore shape and the composition of the gas trapped within the pores are usually not reported. Most authors interested in obtaining usable expressions<sup>[A-2.11 to A-2.14]</sup> have adopted some form of either the modified Loeb equation

$$\frac{K}{K_{100}} = 1 - \alpha P \quad (A-2.8)$$

---

[a] The interested reader will find detailed physical discussions in Reference (A-2.3) and (A-2.4).

or the Maxwell-Eucken equation

$$\frac{K}{K_{100}} = \frac{1 - P}{1 + \beta P} \quad (A-2.9)$$

where

- K = thermal conductivity of a porous sample (W/(mK))
- $K_{100}$  = thermal conductivity of a sample with no pores (W/(mK))
- P = volume of pores/total sample volume (unitless)
- $\alpha, \beta$  = factors depending on the shape and distribution of the pores (unitless).

These authors usually assume  $\alpha$  or  $\beta$  to be linear functions of temperature and fit the linear functions to data from a limited set of samples.

None of the published studies of the effect of porosity on thermal conductivity has used the large collection of data that is available. This will be done in Section 2.3. The correlation will be based on the Maxwell-Eucken relation because the mechanistic studies of both Marino<sup>[A-2.6]</sup> and Ondracek<sup>[A-2.10]</sup> recommend this relation.

The remainder of this literature review will discuss the available experimental measurements of thermal conductivity. Two general types of experiment will be encountered: the radial heat flow method and the transient heat pulse method. In the radial heat flow method heat is supplied internally to a specimen and the thermal conductivity is deduced from measurements of the heat input and the steady-state temperature difference across the sample. In the transient heat pulse method the measured quantity is the thermal diffusivity<sup>[A-2.3]</sup>,

$$\alpha = \frac{K}{C_p \rho} \quad (A-2.10)$$

where

$\alpha$  = thermal diffusivity ( $m^2/sec$ )

$K$  = thermal conductivity ( $W/(mK)$ )

$C_p$  = fuel specific heat at constant pressure ( $J/Kg K$ )

$\rho$  = fuel density ( $kg/m^3$ )

It is interesting to note that as much as 5% of the scatter in the reported values of thermal conductivity is caused by differences in the values of  $C_p$  assumed by authors who rely on thermal diffusivity data.

The available  $UO_2$  data are contained in References A-2.11 to A-2.27. Several of these sources were not used in the present analysis: Hedge<sup>[A-2.15]</sup> and Kingery<sup>[A-2.16]</sup>, used samples with densities between 70 and 75% TD - far below those used in commercial fuel. Asamoto et al<sup>[A-2.14]</sup>, Reisswig<sup>[A-2.23]</sup>, Stora<sup>[A-2.24]</sup> and Hetzler et al<sup>[A-2.17]</sup> employed radial heat flow methods in which the electrically heated center conductor may have been able to contact the oxide sample, so that Joule heating of the oxide could result and indicate anomalously high conductivity. The data of Hetzler and Asamoto also show unusually large scatter, probably because of cracking during the measurements. The data of Ferro et al.,<sup>[A-2.25]</sup> show such large scatter that they were rejected for this reason alone. The data of Lyons et al<sup>[A-2.22]</sup> were derived from observation of postirradiation grain growth and restructuring, a less reliable method than that used by other investigators. The data of Van Craeynest and Stora<sup>[A-2.11]</sup> and Luck and Deem<sup>[A-2.20]</sup> showed anomalously low conductivity compared to data from fuels with similar density. The low conductivity was probably caused by cracking before the reported data were taken.

Christensen's data [A-2.21] are the most suspect of those that were used. The apparatus used in his radial heat flow experiment is not well described. It is possible that the sharp increase in thermal conductivity at high temperature reported by Christensen is due to electrical contact with the heating element. Because of this possibility and because the specimen composition changed from  $UO_{2.01}$  to  $UO_{1.99}$  during the test, Christensen's data for temperatures above 1800 K were not used. The data from Christensen that were used are listed in Table A-2.I.

The data of Godfrey et al [A-2.18] are the most reliable radial heat flow data reviewed in this section. Granular alumina and careful positioning of the center heater were used to minimize electrical contact between the center heater and the sample. Runs which resulted in a change in the oxygen to metal ratio were reported as suspect and not used. Thermocouple errors were analyzed carefully and runs above 1373 K were identified as not valid because of thermocouple problems.

Unfortunately, Godfrey et al used only samples of 93.4% of the theoretical density. Also the data were "corrected to theoretical density" by dividing by the fraction of theoretical density. The unsatisfactory nature of this correction would no doubt have become evident if samples of varying density had been used. This "correction" was removed before the data were used to develop the model described here.

The data with the density correction removed are listed in Table A-2.II. Several runs are represented and there is no systematic variation from run to run. Data at temperatures below 500K are not included in Table A-2.II because the low temperature data cannot be used with Equation (A-2.7) (The equation is valid only when temperatures are well above the Debye Temperature).

The remaining five sets of  $UO_2$  data which were used were all obtained with the heat pulse method. Bates [A-2.19] measured the thermal diffusivity of three samples, all with a density of 98.4% of the theoretical density. Some data which corresponded to runs taken when the samples

TABLE A-2.I

UO<sub>2</sub> DATA FROM CHRISTENSEN (A-2.21)

Temperature (K)	Density (fraction of theoretical)	Thermal Conductivity (w/(mK))
.13120E+04	.9400E+00	.287000E+01
.13890E+04	.9400E+00	.287000E+01
.14320E+04	.9400E+00	.270000E+01
.14960E+04	.9400E+00	.272000E+01
.15520E+04	.9400E+00	.271000E+01
.15870E+04	.9400E+00	.256000E+01
.16120E+04	.9400E+00	.257000E+01
.16560E+04	.9400E+00	.280000E+01
.17470E+04	.9400E+00	.248000E+01
.18380E+04	.9400E+00	.259000E+01

TABLE A-2.II

UO<sub>2</sub> DATA FROM GODFREY ET AL (A-2.18)

Temperature (K)	Density (fraction of theoretical)	Thermal Conductivity (w/(mK))	Run Number
.57400E+03	.9340E+00	.540400E+01	2
.67300E+03	.9340E+00	.575400E+01	
.76700E+03	.9340E+00	.432200E+01	
.87700E+03	.9340E+00	.390200E+01	
.97600E+03	.9340E+00	.355900E+01	
.10740E+04	.9340E+00	.326500E+01	
.67500E+03	.9340E+00	.461000E+01	3
.87000E+03	.9340E+00	.379400E+01	
.86900E+03	.9340E+00	.383200E+01	
.97100E+03	.9340E+00	.348700E+01	
.10720E+04	.9340E+00	.318200E+01	
.11650E+04	.9340E+00	.298500E+01	
.11730E+04	.9340E+00	.297500E+01	
.12790E+04	.9340E+00	.277400E+01	
.12820E+04	.9340E+00	.275500E+01	
.57200E+03	.9340E+00	.516700E+01	4
.87000E+03	.9340E+00	.373700E+01	
.87000E+03	.9340E+00	.369000E+01	
.87200E+03	.9340E+00	.368100E+01	
.11710E+04	.9340E+00	.288800E+01	
.11750E+04	.9340E+00	.287000E+01	
.57000E+03	.9340E+00	.514000E+01	
.57200E+03	.9340E+00	.511100E+01	
.67300E+03	.9340E+00	.458900E+01	
.67300E+03	.9340E+00	.455700E+01	
.77400E+03	.9340E+00	.407700E+01	
.77400E+03	.9340E+00	.409600E+01	
.87500E+03	.9340E+00	.371100E+01	
.87500E+03	.9340E+00	.373400E+01	
.97300E+03	.9340E+00	.341600E+01	
.97300E+03	.9340E+00	.341700E+01	
.10710E+04	.9340E+00	.316900E+01	
.10710E+04	.9340E+00	.316900E+01	
.11730E+04	.9340E+00	.295000E+01	
.12710E+04	.9340E+00	.275100E+01	
.13230E+04	.9340E+00	.268200E+01	
.57600E+03	.9340E+00	.523200E+01	6
.57600E+03	.9340E+00	.522900E+01	
.67100E+03	.9340E+00	.469100E+01	
.67100E+03	.9340E+00	.469100E+01	
.67100E+03	.9340E+00	.470500E+01	
.87400E+03	.9340E+00	.382100E+01	

had a metallic second phase at the grain boundaries were not used. Table A-2.III is a list of the values of thermal conductivity deduced from Bates' thermal diffusivity data, Equation (A-2.10), and the MATPRO expressions for fuel specific heat at constant pressure and thermal expansion<sup>[a]</sup>. There is no systematic variation in the data either from run to run or sample to sample.

Gibby<sup>[A-2.27]</sup> reported the thermal diffusivity of a UO<sub>2</sub> sample as part of a study on the effect of plutonium additions. The sample had a density of 95.8% of the theoretical density. The thermal conductivity calculated from Gibby's diffusivities are shown in Table A-2.IV.

Weilbacher<sup>[A-2.26]</sup> reported the thermal diffusivity of a UO<sub>2</sub> sample as part of a study of the effect of thorium additions. The sample had a density of 98.0% of the theoretical density. The data are important because they include temperatures up to melting and because the low temperature part of the data fall within the narrow scatter of the data reported by Bates for his samples of similar density. The close agreement of the two sets of data provide support for the idea that recent thermal diffusivity data on uncracked samples is more consistent than had been previously expected. The thermal conductivity calculated from Weilbacher's thermal diffusivity data using the same MATPRO expressions that were used with Bates' data are listed in Table A-2.V.

[a] The expressions for UO<sub>2</sub> specific heat and thermal expansion are

$$C_p = \frac{296.7 (535.285)^2}{T^2 \left( \exp \left( \frac{535.285}{T} \right) - 1 \right)^2} \exp \left( \frac{535.285}{T} \right) + 2.43 \cdot 10^{-2} T$$

$$+ \frac{8.745 \cdot 10^7 \cdot 1.577}{T^2} \exp \left( \frac{-1.577 \cdot 10^5}{8.3143 T} \right) \quad (A-2.11)$$

$$\text{and } e_{th} = 10^{-5} T - 3 \cdot 10^{-3} + 4 \cdot 10^{-2} \exp \left( -\frac{6.9 \cdot 10^{-20}}{1.38 \cdot 10^{-23} T} \right) \quad (A-2.12)$$

where  $C_p$  = UO<sub>2</sub> specific heat (J/(kg K))

$e_{th}$  = linear strain caused by thermal expansion (unitless)

T = temperature (K)

TABLE A-2.III

UO<sub>2</sub> DATA FROM BATES (A-2.19) THERMAL DIFFUSIVITY MEASUREMENTS

Temperature (K)	Density (fraction of theoretical)	Thermal Conductivity (w/(mK))	Sample	Cycle Number
.53900E+03	.9840E+00	.65000E+01	RR1	3
.53900E+03	.9840E+00	.65700E+01		
.75600E+03	.9840E+00	.48200E+01		
.76100E+03	.9840E+00	.50200E+01		
.89500E+03	.9840E+00	.41100E+01		
.89100E+03	.9840E+00	.43500E+01		
.99400E+03	.9840E+00	.38300E+01		
.99500E+03	.9840E+00	.39100E+01		
.11800E+04	.9840E+00	.32800E+01		
.11850E+04	.9840E+00	.31300E+01		
.13250E+04	.9840E+00	.28500E+01		
.13250E+04	.9840E+00	.28900E+01		
.14890E+04	.9840E+00	.25100E+01		
.14910E+04	.9840E+00	.25500E+01		
.16660E+04	.9840E+00	.24000E+01		
.16550E+04	.9840E+00	.23700E+01		
.17780E+04	.9840E+00	.22400E+01		
.17800E+04	.9840E+00	.21300E+01		
.18630E+04	.9840E+00	.21900E+01		
.18660E+04	.9840E+00	.21900E+01		
.19770E+04	.9840E+00	.21000E+01		
.19720E+04	.9840E+00	.22400E+01		
.20930E+04	.9840E+00	.23200E+01		
.21020E+04	.9840E+00	.22500E+01		
.21740E+04	.9840E+00	.22600E+01		
.21870E+04	.9840E+00	.22500E+01		
.23730E+04	.9840E+00	.24900E+01		
.23730E+04	.9840E+00	.26400E+01		
.22800E+04	.9840E+00	.22900E+01		
.22850E+04	.9840E+00	.24200E+01		
.15990E+04	.9840E+00	.23700E+01		
.16010E+04	.9840E+00	.24900E+01		
.16090E+04	.9840E+00	.23200E+01		
.13600E+04	.9840E+00	.28300E+01	RR1	4
.14530E+04	.9840E+00	.24200E+01		
.15620E+04	.9840E+00	.24800E+01		
.16490E+04	.9840E+00	.23700E+01		
.17500E+04	.9840E+00	.23900E+01		
.19070E+04	.9840E+00	.21300E+01		
.20050E+04	.9840E+00	.21000E+01		
.20070E+04	.9840E+00	.23100E+01		
.21090E+04	.9840E+00	.21900E+01		
.21040E+04	.9840E+00	.22700E+01		
.21950E+04	.9840E+00	.23500E+01		
.22950E+04	.9840E+00	.24700E+01		
.23840E+04	.9840E+00	.24200E+01		

TABLE A-2.III (cont...)

Temperature (K)	Density (fraction of theoretical)	Thermal Conductivity (w/(mk))	Sample	Cycle Number
.57100E+03	.9840E+00	.572000E+01	RR2	2
.57700E+03	.9840E+00	.603000E+01		
.57700E+03	.9840E+00	.616000E+01		
.66100E+03	.9840E+00	.533000E+01		
.68200E+03	.9840E+00	.541000E+01		
.78600E+03	.9840E+00	.448000E+01		
.78400E+03	.9840E+00	.445000E+01		
.78500E+03	.9840E+00	.454000E+01		
.86600E+03	.9840E+00	.415000E+01		
.86700E+03	.9840E+00	.415000E+01		
.96100E+03	.9840E+00	.373000E+01		
.96100E+03	.9840E+00	.363000E+01		
.96100E+03	.9840E+00	.396000E+01		
.10690E+04	.9840E+00	.335000E+01		
.10710E+04	.9840E+00	.331000E+01		
.10690E+04	.9840E+00	.351000E+01		
.11710E+04	.9840E+00	.304000E+01		
.11740E+04	.9840E+00	.307000E+01		
.11710E+04	.9840E+00	.324000E+01		
.12700E+04	.9840E+00	.280000E+01		
.12690E+04	.9840E+00	.287000E+01		
.12700E+04	.9840E+00	.281000E+01		
.13610E+04	.9840E+00	.255000E+01		
.13610E+04	.9840E+00	.263000E+01		
.13600E+04	.9840E+00	.259000E+01		
.13610E+04	.9840E+00	.263000E+01		
.14710E+04	.9840E+00	.254000E+01		
.14720E+04	.9840E+00	.267000E+01		
.14690E+04	.9840E+00	.226000E+01		
.15690E+04	.9840E+00	.240000E+01		
.15710E+04	.9840E+00	.241000E+01		
.15690E+04	.9840E+00	.246000E+01		
.16830E+04	.9840E+00	.233000E+01		
.16830E+04	.9840E+00	.237000E+01		
.17580E+04	.9840E+00	.230000E+01		
.17560E+04	.9840E+00	.219000E+01		
.17600E+04	.9840E+00	.228000E+01		
.67300E+03	.9840E+00	.553000E+01	RR2	3
.12830E+04	.9840E+00	.275000E+01		
.67300E+03	.9840E+00	.542000E+01		
.11000E+04	.9840E+00	.360000E+01	RR3	1
.10890E+04	.9840E+00	.340000E+01		
.10900E+04	.9840E+00	.354000E+01		
.10990E+04	.9840E+00	.341000E+01		
.81300E+03	.9840E+00	.486000E+01		
.79700E+03	.9840E+00	.480000E+01		

TABLE A-2.III (cont...)

Temperature (K)	Density (fraction of theoretical)	Thermal Conductivity (w/(mK))	Sample	Cycle Number		
.58700E+03	.9840E+00	.646000E+01	RR3	2		
.58300E+03	.9840E+00	.640000E+01				
.67600E+03	.9840E+00	.542000E+01				
.67900E+03	.9840E+00	.551000E+01				
.76300E+03	.9840E+00	.501000E+01				
.76400E+03	.9840E+00	.513000E+01				
.87300E+03	.9840E+00	.450000E+01				
.87600E+03	.9840E+00	.429000E+01				
.97900E+03	.9840E+00	.395000E+01				
.98100E+03	.9840E+00	.396000E+01				
.10650E+04	.9840E+00	.374000E+01				
.10720E+04	.9840E+00	.369000E+01				
.11880E+04	.9840E+00	.317000E+01				
.11870E+04	.9840E+00	.336000E+01				
.12770E+04	.9840E+00	.309000E+01				
.12850E+04	.9840E+00	.319000E+01				
.12840E+04	.9840E+00	.328000E+01				
.10710E+04	.9840E+00	.370000E+01				
.88000E+03	.9840E+00	.457000E+01				
.87900E+03	.9840E+00	.452000E+01				
.87900E+03	.9840E+00	.452000E+01				
.67800E+03	.9840E+00	.534000E+01				
.54900E+03	.9840E+00	.634000E+01				
.57300E+03	.9840E+00	.618000E+01			RR3	3
.58300E+03	.9840E+00	.589000E+01				
.68000E+03	.9840E+00	.536000E+01				
.68100E+03	.9840E+00	.524000E+01				
.67800E+03	.9840E+00	.533000E+01				
.77600E+03	.9840E+00	.488000E+01				
.77500E+03	.9840E+00	.494000E+01				
.89100E+03	.9840E+00	.417000E+01				
.89500E+03	.9840E+00	.430000E+01				
.96800E+03	.9840E+00	.398000E+01				
.97300E+03	.9840E+00	.396000E+01				
.10870E+04	.9840E+00	.345000E+01				
.10810E+04	.9840E+00	.348000E+01				
.11720E+04	.9840E+00	.324000E+01				
.11730E+04	.9840E+00	.316000E+01				
.12920E+04	.9840E+00	.285000E+01				
.12910E+04	.9840E+00	.281000E+01				
.13770E+04	.9840E+00	.265000E+01				
.13800E+04	.9840E+00	.263000E+01				
.14730E+04	.9840E+00	.254000E+01				
.14770E+04	.9840E+00	.259000E+01				
.15780E+04	.9840E+00	.230000E+01				
.15840E+04	.9840E+00	.245000E+01				
.16730E+04	.9840E+00	.223000E+01				
.16790E+04	.9840E+00	.220000E+01				
.17690E+04	.9840E+00	.209000E+01				
.17920E+04	.9840E+00	.224000E+01				
.17860E+04	.9840E+00	.219000E+01				
.15950E+04	.9840E+00	.246000E+01				
.15960E+04	.9840E+00	.241000E+01				
.14000E+04	.9840E+00	.261000E+01				
.13990E+04	.9840E+00	.256000E+01				
.11660E+04	.9840E+00	.329000E+01				
.10790E+04	.9840E+00	.344000E+01				
.10850E+04	.9840E+00	.350000E+01				
.84700E+03	.9840E+00	.443000E+01				
.84700E+03	.9840E+00	.445000E+01				
.57700E+03	.9840E+00	.598000E+01				
.55300E+03	.9840E+00	.622000E+01				

TABLE A-2.IV

UO<sub>2</sub> DATA FROM GIBBY'S (A-2.27) THERMAL DIFFUSIVITY MEASUREMENTS

Temperature (K)	Density (fraction of theoretical)	Thermal Conductivity (w/(mK))
.57500E+03	.9580E+00	.624000E+01
.57800E+03	.9580E+00	.636000E+01
.58600E+03	.9580E+00	.628000E+01
.58700E+03	.9580E+00	.587000E+01
.58800E+03	.9580E+00	.563000E+01
.66500E+03	.9580E+00	.512000E+01
.67500E+03	.9580E+00	.520000E+01
.67900E+03	.9580E+00	.531000E+01
.69000E+03	.9580E+00	.512000E+01
.84600E+03	.9580E+00	.430000E+01
.84600E+03	.9580E+00	.440000E+01
.85200E+03	.9580E+00	.453000E+01
.85300E+03	.9580E+00	.465000E+01
.86500E+03	.9580E+00	.430000E+01
.86500E+03	.9580E+00	.440000E+01
.89300E+03	.9580E+00	.429000E+01
.90800E+03	.9580E+00	.429000E+01
.90700E+03	.9580E+00	.420000E+01
.96400E+03	.9580E+00	.384000E+01
.96400E+03	.9580E+00	.392000E+01
.96900E+03	.9580E+00	.402000E+01
.96900E+03	.9580E+00	.412000E+01
.10000E+04	.9580E+00	.370000E+01
.10310E+04	.9580E+00	.394000E+01
.10310E+04	.9580E+00	.384000E+01
.10710E+04	.9580E+00	.366000E+01
.10800E+04	.9580E+00	.347000E+01
.10800E+04	.9580E+00	.355000E+01
.12040E+04	.9580E+00	.324000E+01
.12040E+04	.9580E+00	.334000E+01
.12800E+04	.9580E+00	.313000E+01
.12880E+04	.9580E+00	.299000E+01
.12880E+04	.9580E+00	.292000E+01
.12890E+04	.9580E+00	.299000E+01
.13230E+04	.9580E+00	.301000E+01
.13350E+04	.9580E+00	.290000E+01
.13840E+04	.9580E+00	.292000E+01
.13900E+04	.9580E+00	.280000E+01
.13950E+04	.9580E+00	.270000E+01
.13990E+04	.9580E+00	.280000E+01
.14120E+04	.9580E+00	.295000E+01
.14910E+04	.9580E+00	.278000E+01
.15020E+04	.9580E+00	.244000E+01
.15080E+04	.9580E+00	.262000E+01
.15100E+04	.9580E+00	.266000E+01

TABLE A-2.V

UO<sub>2</sub> DATA FROM WEILBACHER'S (A-2.26) THERMAL DIFFUSIVITY MEASUREMENTS

Temperature (K)	Density (fraction of theoretical)	Thermal Conductivity (w/(mK))
.97400E+03	.9800E+00	.358000E+01
.97400E+03	.9800E+00	.381000E+01
.11710E+04	.9800E+00	.309000E+01
.11710E+04	.9800E+00	.325000E+01
.13770E+04	.9800E+00	.262000E+01
.13700E+04	.9800E+00	.285000E+01
.15750E+04	.9800E+00	.231000E+01
.15750E+04	.9800E+00	.251000E+01
.17780E+04	.9800E+00	.218000E+01
.17780E+04	.9800E+00	.239000E+01
.19790E+04	.9800E+00	.219000E+01
.19800E+04	.9800E+00	.233000E+01
.21800E+04	.9800E+00	.226000E+01
.21820E+04	.9800E+00	.239000E+01
.22810E+04	.9800E+00	.231000E+01
.22840E+04	.9800E+00	.245000E+01
.23790E+04	.9800E+00	.245000E+01
.23790E+04	.9800E+00	.254000E+01
.24840E+04	.9800E+00	.261000E+01
.24830E+04	.9800E+00	.273000E+01
.25770E+04	.9800E+00	.274000E+01
.25770E+04	.9800E+00	.286000E+01
.26740E+04	.9800E+00	.291000E+01
.26740E+04	.9800E+00	.302000E+01
.27730E+04	.9800E+00	.310000E+01
.27730E+04	.9800E+00	.321000E+01
.28750E+04	.9800E+00	.332000E+01
.28750E+04	.9800E+00	.344000E+01
.30250E+04	.9800E+00	.366000E+01
.30270E+04	.9800E+00	.383000E+01

The data of Goldsmith and Douglas<sup>[A-2.12]</sup> provide more support for the idea that recent thermal diffusivity data on uncracked samples are more consistent than previously reported. When the MATPRO expressions for specific heat and thermal expansion are employed to convert the thermal diffusivity data of Goldsmith and Douglas to thermal conductivity, the resultant thermal conductivities fall within the scatter of the data of several authors who performed extensive measurements on a limited number of samples. The thermal conductivities obtained from Goldsmith and Douglas' data are presented in Table A-2.VI. The thermal conductivity data from the 98.2 and 97.7% of theoretical density samples agree with the data of Bates and Weilbacher, the 95.1 and 95.8% dense sample data agree with the data of Gibby, the 95.2 and 94.7% dense sample data agree with the data of Hobson et al<sup>[A-2.13]</sup> (which will be discussed in the next paragraph), and the 93.2% and 93.0% dense sample data agree with the data of Godfrey<sup>[a]</sup>.

The final set of  $UO_2$  data to be discussed are those of I. C. Hobson et al<sup>[A-2.13]</sup>. These authors have apparently measured the thermal diffusivity of a series of  $UO_2$  samples. However, they reported only data from a single sample of density  $10.40 \times 10^3 \text{ Kg/m}^3$  (94.9% of theoretical density). The remainder of their results are reported as correlations, a format which renders their work useless for the purpose of this report. The usable thermal diffusivity data were converted to thermal conductivity and are listed in Table A-2.VII.

The data appropriate for modeling the thermal conductivity of mixed  $(U,Pu)O_{2+x}$  include the available  $(U,Pu)O_2$  measurements<sup>[A-2.11,A-2.17,A-2.27 to A-2.34]</sup> and  $UO_{2+x}$  data with  $x \neq 0$ <sup>[A-2.12,A-2.13,A-2.17]</sup>. The  $UO_{2+x}$  data are important because the effect of non-stoichiometry in mixed oxide fuels is at least as important as the effect of variations in the weight fraction of  $PuO_2$ . Unfortunately, the limited resources available to produce the present model preclude a careful review of the

---

[a] The thermal conductiveness determined from each author's data will be compared with each other and the MATPRO model in a series of figures presented in Section 2.4.

TABLE A-2.VI

UO<sub>2</sub> DATA FROM GOLDSMITH AND DOUGLAS<sup>1</sup> (A-2.12) THERMAL DIFFUSIVITY MEASUREMENTS

Temperature (K)	Density (fraction of theoretical)	Thermal Conductivity (w/(mK))
.6700E+03	.9860E+00	.557000E+01
.6700E+03	.9860E+00	.553000E+01
.6700E+03	.9860E+00	.559000E+01
.6700E+03	.9820E+00	.531000E+01
.6700E+03	.9770E+00	.543000E+01
.6700E+03	.9610E+00	.519000E+01
.6700E+03	.9580E+00	.498000E+01
.6700E+03	.9520E+00	.485000E+01
.6700E+03	.9470E+00	.508000E+01
.6700E+03	.9320E+00	.455000E+01
.6700E+03	.9300E+00	.461000E+01
.6700E+03	.9060E+00	.440000E+01
.6700E+03	.9040E+00	.420000E+01
.8700E+03	.9860E+00	.468000E+01
.8700E+03	.9860E+00	.467000E+01
.8700E+03	.9860E+00	.470000E+01
.8700E+03	.9820E+00	.444000E+01
.8700E+03	.9770E+00	.460000E+01
.8700E+03	.9610E+00	.438000E+01
.8700E+03	.9580E+00	.410000E+01
.8700E+03	.9520E+00	.416000E+01
.8700E+03	.9470E+00	.426000E+01
.8700E+03	.9320E+00	.380000E+01
.8700E+03	.9300E+00	.388000E+01
.8700E+03	.9060E+00	.369000E+01
.8700E+03	.9040E+00	.349000E+01
.1070E+04	.9860E+00	.396000E+01
.1070E+04	.9860E+00	.394000E+01
.1070E+04	.9860E+00	.394000E+01
.1070E+04	.9820E+00	.375000E+01
.1070E+04	.9770E+00	.387000E+01
.1070E+04	.9610E+00	.370000E+01
.1070E+04	.9580E+00	.356000E+01
.1070E+04	.9520E+00	.346000E+01
.1070E+04	.9470E+00	.361000E+01
.1070E+04	.9320E+00	.324000E+01
.1070E+04	.9300E+00	.330000E+01
.1070E+04	.9060E+00	.310000E+01
.1070E+04	.9040E+00	.291000E+01
.1270E+04	.9860E+00	.327000E+01
.1270E+04	.9860E+00	.326000E+01
.1270E+04	.9860E+00	.332000E+01
.1270E+04	.9820E+00	.316000E+01
.1270E+04	.9770E+00	.323000E+01
.1270E+04	.9610E+00	.312000E+01
.1270E+04	.9580E+00	.301000E+01
.1270E+04	.9520E+00	.295000E+01
.1270E+04	.9470E+00	.301000E+01
.1270E+04	.9320E+00	.266000E+01
.1270E+04	.9300E+00	.275000E+01
.1270E+04	.9060E+00	.259000E+01
.1270E+04	.9040E+00	.246000E+01

TABLE A-2.VII

UO<sub>2</sub> DATA FROM HOBSON ET AL'S (A-2.13) THERMAL DIFFUSIVITY MEASUREMENTS

Temperature (K)	Density (fraction of theoretical)	Thermal Conductivity (w/(mK))
.5670E+03	.9490E+00	.576000E+01
.6070E+03	.9490E+00	.541000E+01
.6420E+03	.9490E+00	.533000E+01
.7320E+03	.9490E+00	.496000E+01
.7880E+03	.9490E+00	.463000E+01
.8340E+03	.9490E+00	.445000E+01
.8850E+03	.9490E+00	.426000E+01
.9440E+03	.9490E+00	.413000E+01
.9950E+03	.9490E+00	.401000E+01
.1046E+04	.9490E+00	.386000E+01
.1083E+04	.9490E+00	.375000E+01
.1133E+04	.9490E+00	.362000E+01
.1150E+04	.9490E+00	.351000E+01
.1175E+04	.9490E+00	.353000E+01
.1279E+04	.9490E+00	.323000E+01
.1330E+04	.9490E+00	.315000E+01
.1392E+04	.9490E+00	.304000E+01
.1449E+04	.9490E+00	.297000E+01
.1500E+04	.9490E+00	.281000E+01
.1532E+04	.9490E+00	.284000E+01
.1621E+04	.9490E+00	.263000E+01
.1638E+04	.9490E+00	.269000E+01
.1749E+04	.9490E+00	.252000E+01
.1760E+04	.9490E+00	.258000E+01
.1807E+04	.9490E+00	.246000E+01
.1871E+04	.9490E+00	.260000E+01
.1913E+04	.9490E+00	.248000E+01
.1993E+04	.9490E+00	.245000E+01
.2016E+04	.9490E+00	.252000E+01
.2059E+04	.9490E+00	.247000E+01
.2154E+04	.9490E+00	.243000E+01
.2154E+04	.9490E+00	.249000E+01
.2243E+04	.9490E+00	.247000E+01
.2336E+04	.9490E+00	.251000E+01
.2412E+04	.9490E+00	.263000E+01
.2503E+04	.9490E+00	.266000E+01

(U,Pu)O<sub>2+x</sub> or the UO<sub>2+x</sub> data. For that reason the stoichiometric data from References A-2.27 to A-2.30 and the model proposed by Olander<sup>[A-2.1]</sup> for the effect of oxygen-to-metal ratio variations will be adopted without modification.

### 2.3 Model Development

The development of the model for thermal conductivity of (U,Pu)O<sub>2+x</sub> was based directly on the theory and data which have just been reviewed. The first step in producing the model was the determination of an expression for the effect of density. The UO<sub>2</sub> data were grouped by density and second degree polynomials in temperature were fit to the data in each group. Inspection of the data<sup>[a]</sup> revealed a regular pattern of decreasing thermal conductivity with decreasing density at low temperature but almost no effect of density at high temperature. For this reason, the polynomials representing the thermal conductivity of the various groups were evaluated at 600 and 1000 K and the average thermal conductivities obtained were used with Equation (A-2.9) to obtain linear functions of the form

$$\beta = \beta_0 + \beta_1 T \quad (A-2.13)$$

corresponding to pairs of porosity groups. The resultant values of  $\beta_0$  and  $\beta_1$  are listed in Table 2.VIII.

The scatter in the values of  $\beta_0$  and  $\beta_1$  is caused by unknown variations of pore shape and content as discussed in Section 2.2. In subsequent model development steps all three sets of  $\beta_0$  and  $\beta_1$  as well as their average values were tested to see which produced the model with the smallest standard error. Very little difference was found so the average values of  $\beta_0$  and  $\beta_1$  were adopted.

---

[a] The data and model predictions are illustrated in Figures A-2.1 to A-2.8 of Section 2.4.

TABLE A-2.VIII

VALUES OF  $\beta_0$  AND  $\beta_1$  FROM VARIOUS DENSITY GROUPS

<u>Groups Compared</u> <sup>a</sup>	<u><math>\beta_0</math></u>	<u><math>\beta_1</math></u>
2 and 5	9.6	-0.00946
2 and 7	4.1	-0.00281
4 and 7	5.8	-0.00181
Averages	6.5	-0.00469

<sup>a</sup> Group 2 contains densities between 0.975 and 0.985 of theoretical  
 Group 4 contains densities between 0.955 and 0.965 of theoretical  
 Group 5 contains densities between 0.945 and 0.955 of theoretical  
 Group 7 contains densities between 0.925 and 0.935 of theoretical

The second step in the development of the model was the determination of the constants A and B of Equation (A-2.7). This was done with a least squares fitting technique and the  $UO_2$  thermal conductivity data for temperatures between 500 and 1100 K<sup>[a]</sup>. The data were normalized to 100% of theoretical density with Equation (A-2.9) before the fit was carried out.

The third step in developing the  $UO_2$  model was the determination of a value of the constant f in Equation (A-2.6) with the high temperature data. Since Equation (A-2.6) models the electronic contribution to thermal conductivity, a value of f was determined with a least squares fit to the difference between the experimental thermal conductivities and the lattice vibration contribution predicted with Equation (A-2.7). The factor  $A + BT$  in Equation (A-2.7) was limited to its value at  $T = 2050$  K because the mean free path of the phonons is about equal to the inter-atomic distance at this temperature<sup>[A-2.1]</sup>. No normalization for density was applied to the high temperature data.

The final steps in the development of the  $UO_2$  model were a trivial smoothing of two discontinuities in the slope of the predicted thermal conductivities as a function of temperature and the provision of an estimate for liquid fuel. The discontinuities are caused by limiting the  $\beta$  in Equation (A-2.9) to values larger than -1 and limiting the phonon mean free path to at least the interatomic distance. Each discontinuity was removed by replacing temperature with an interpolated temperature in a range about the cut-off value and requiring the interpolated temperature to produce continuous functions and slopes at the ends of the range. For liquid fuel, the lattice vibration contribution to thermal conductivity was set equal to zero.

Several preliminary assumptions have been made to provide at least an approximate model for the effects of variations in the plutonium content and the oxygen-to-metal ratio of ceramic fuels:

---

[a] Data below 500 K were not used because Equation (A-2.7) is not valid near the Debye temperature.

- (a) The effect of variations in density of mixed oxide fuels has been assumed to be described by the porosity correction derived with  $UO_2$  data.
- (b) The high temperature electronic contribution to thermal conductivity has been assumed to be similar for  $PuO_2$ ,  $UO_2$  and non-stoichiometric fuels.
- (c) Variations in plutonium content have been assumed to affect only the phonon-phonon scattering term of Equation (A-2.7).
- (d) Variations in oxygen to metal ratio have been assumed to affect only the defect term of Equation (A-2.7).

The change in the phonon-phonon scattering term of Equation (A-2.7) was modeled by fitting reported thermal conductivities of  $(U,Pu)O_2$  [A-2.27 to 2.30, A-2.33] to Equation (A-2.7) with B replaced by

$$B' = B_{UO_2} (1 + b \text{ COMP}) \quad (\text{A-2.14})$$

where

- $B'$  = coefficient of temperature in Equation (A-2.7) for mixed oxides
- $B_{UO_2}$  = coefficient of temperature in Equation (A-2.7) for  $UO_2$
- COMP =  $PuO_2$  content of the fuel (ratio of weight of  $PuO_2$  to total weight)
- $b$  = constant to be determined.

The resultant value of  $b$  was 0.6238.

Olander's expression<sup>[A-2.1]</sup> for the effect of oxygen-to-metal ratio on the defect term of Equation (A-2.7) was adopted to provide a preliminary model for the effect of variations from stoichiometry. The fractional change in the defect term was estimated by Olander to be

$$\frac{\Delta A}{A} = \frac{400X}{A'} \quad (\text{A-2.15})$$

where

X = departure from an oxygen-to-metal ratio of 2

A' = defect term in Olander's version of Equation (A-2.7)

$\frac{\Delta A}{A}$  = fractional change in the defect term of Equation (A-2.7)

The expression for A which resulted from this adaptation is given in Equation (A-2.1).

#### 2.4 Uncertainty of the Model

The standard error<sup>[a]</sup> of the FTHCON model for thermal conductivity with respect to its UO<sub>2</sub> data base is  $\pm 0.20$  W/(mK). The standard error with respect to the (U,Pu)O<sub>2</sub> data base is  $\pm 0.29$  W/(mK). The first two terms of Equation (A-2.2), the expression for model uncertainty which has been added to the FTHCON subcode, were constructed to reproduce these uncertainties at 0 and 20% PuO<sub>2</sub> content. The third term of Equation (A-2.2) provides an engineering estimate of the increase in the error of the model for non-stoichiometric fuel.

Figures A-2.1 to A-2.8 illustrate the model predictions and the UO<sub>2</sub> data base for several densities. Each figure shows data within  $\pm 0.05$  of the fraction of theoretical density assumed for the model prediction.

[a] The standard error was estimated with the expression (sum of squared residuals/number of residuals minus the number of constants used to fit the data)<sup>0.5</sup>. Five constants were used for the UO<sub>2</sub> data and six were used for the PuO<sub>2</sub> data.

11-23-94 THUR 1 FEB. 1979 JOB=MMMS30 . IL DISPLA VER 7.3

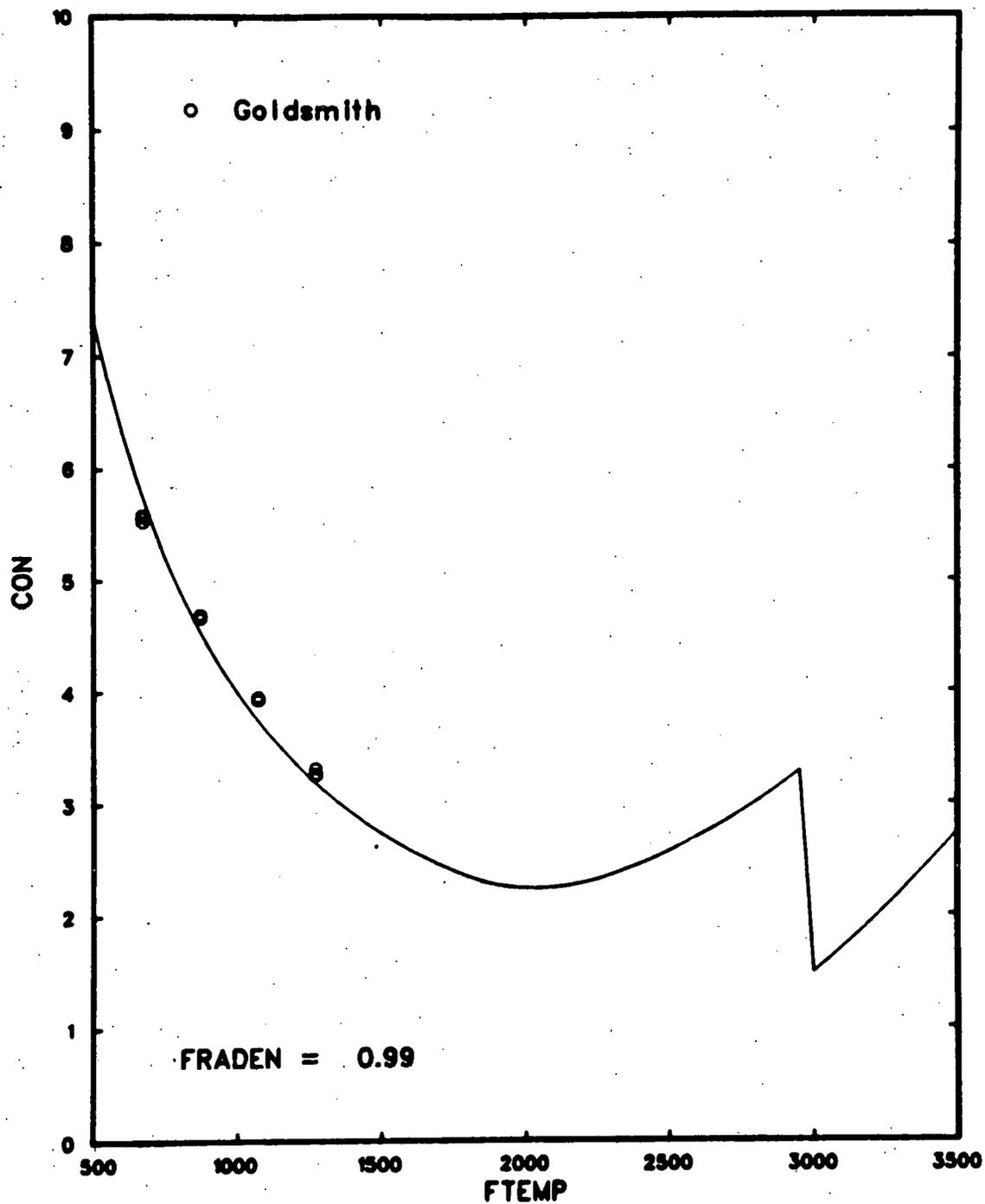


Fig. A-2.1 Model prediction for thermal conductivity of 0.99 of theoretical density UO<sub>2</sub> compared to data from specimens with densities in the range 0.985 to 0.995 of theoretical density.

PLOT 2 11.23.85 TIME 1 FEB. 1979 JOB=HND050 . IL DISPLA VCR 7.3

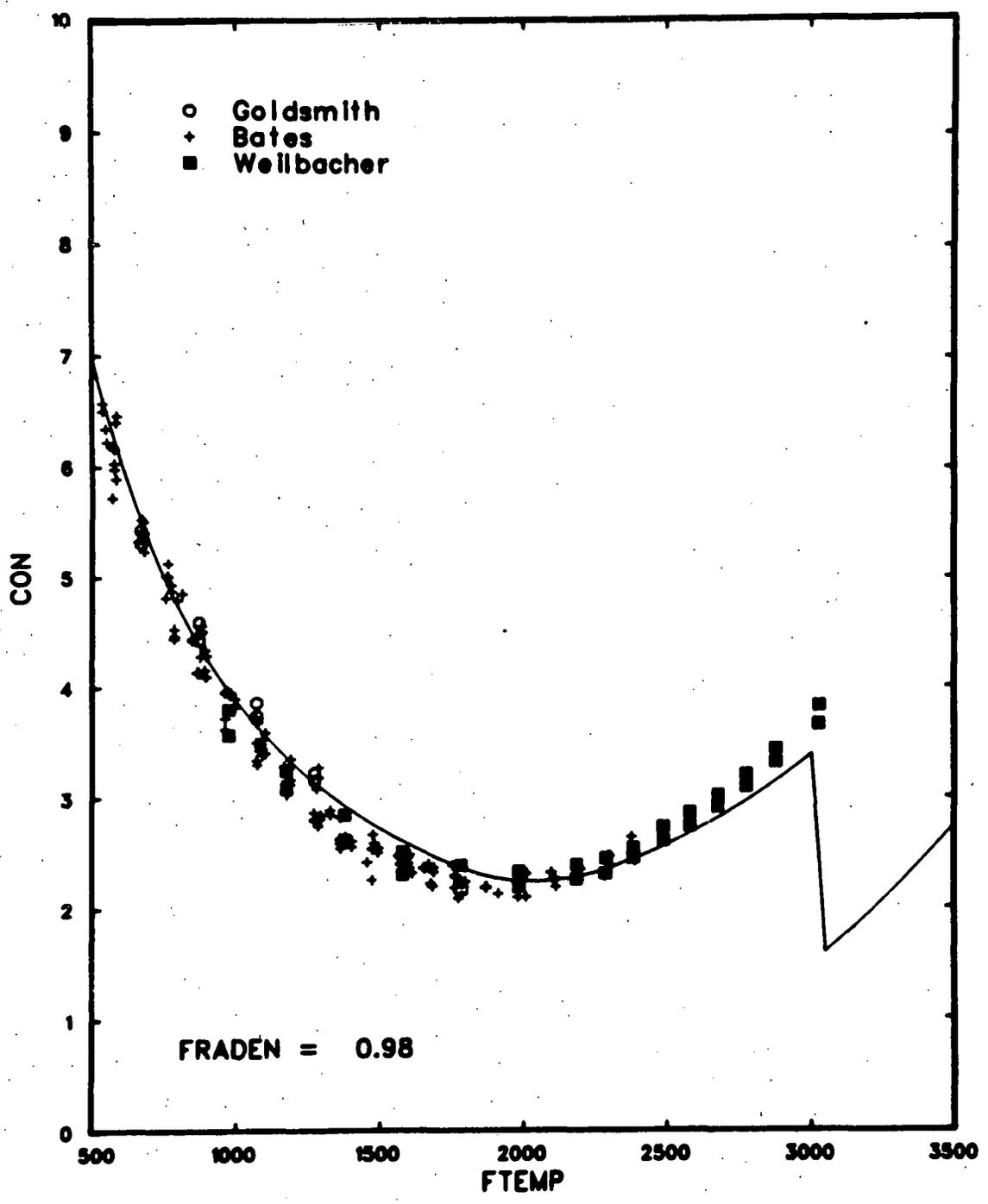


Fig. A-2.2 Model prediction for thermal conductivity of 0.98 of theoretical density  $UO_2$  compared to data from specimens with densities in the range of 0.975 to 0.985 of theoretical density.

PLOT 4 11.23.46 TMR 1 FEB. 1979 JOB=HWDF30 . IL DISPLA VER 7.3

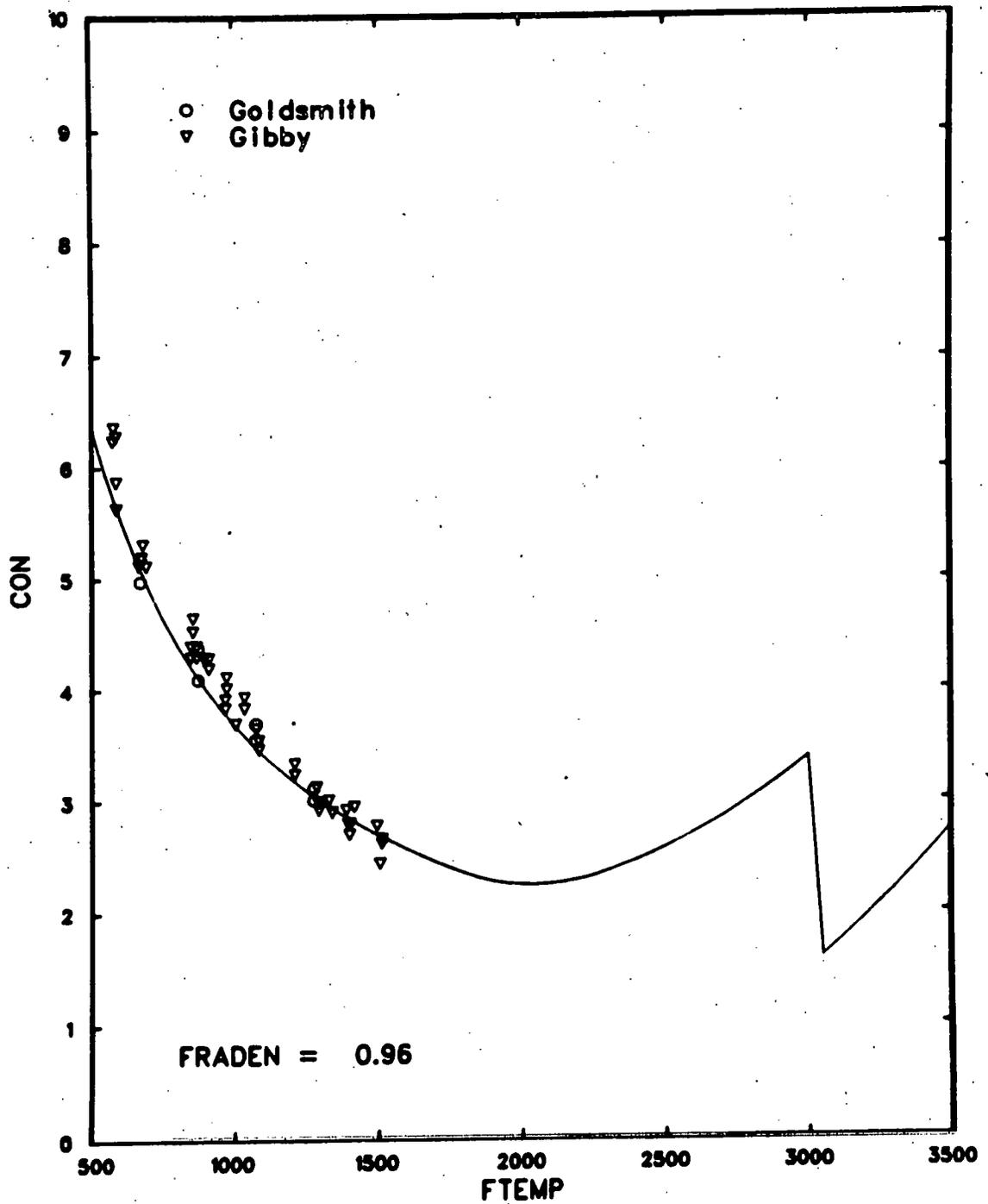


Fig. A-2.3 Model prediction for thermal conductivity of 0.96 of theoretical density UO<sub>2</sub> compared to data from specimens with densities in the range 0.955 to 0.965 of theoretical density.

PLOT 5 17.02.13 TRUP 1 FEB, 1979 JOB=MEMO21 . IL 0155PLA VER 7.3

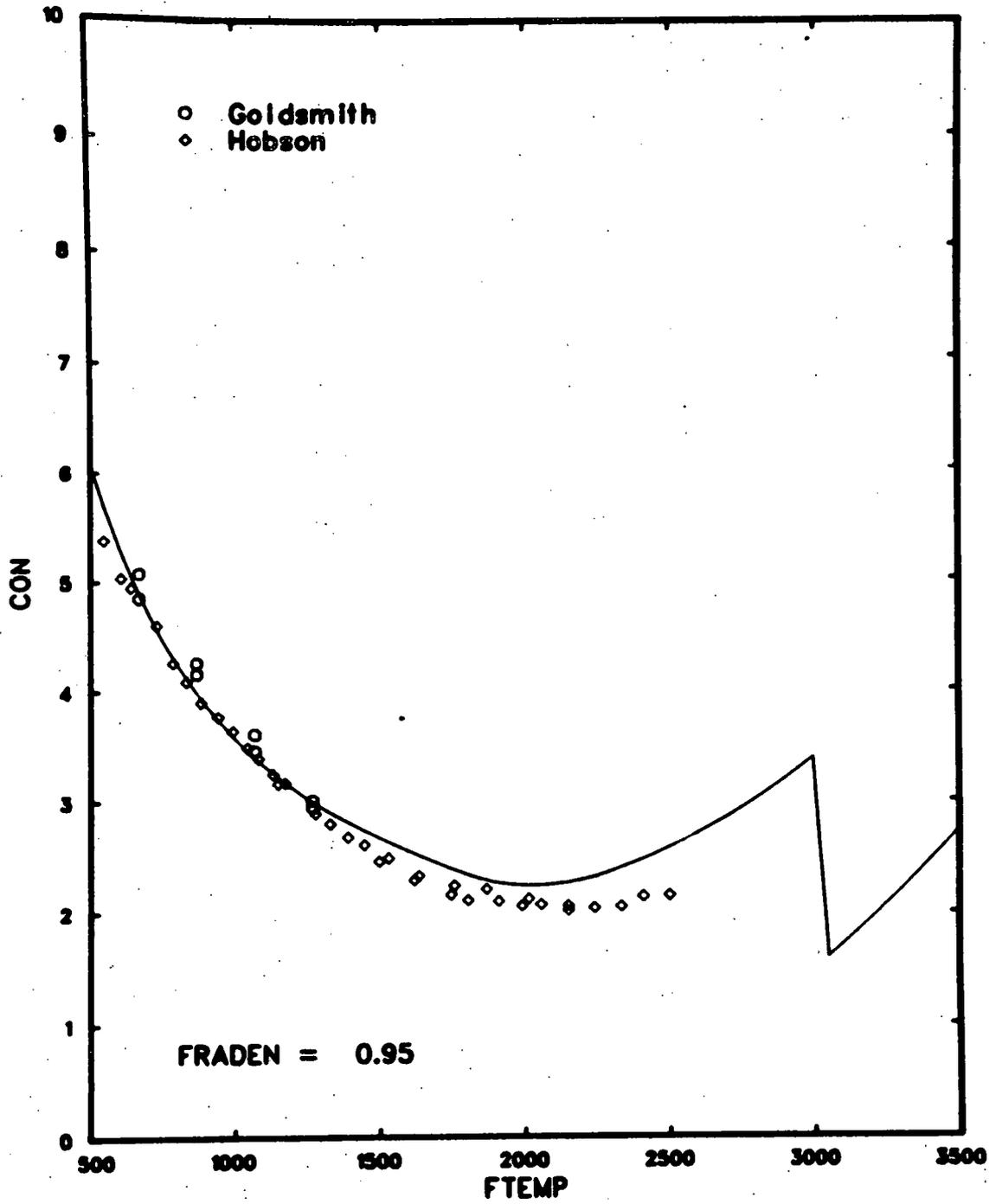


Fig. A-2.4 Model prediction for thermal conductivity of 0.95 of theoretical density  $UO_2$  compared to data from specimens with densities in the range 0.945 to 0.955 of theoretical density.

11.23.17 TIME 1 FEB. 1979 JOB=MM0050 . IL DISPLA PER 7.3

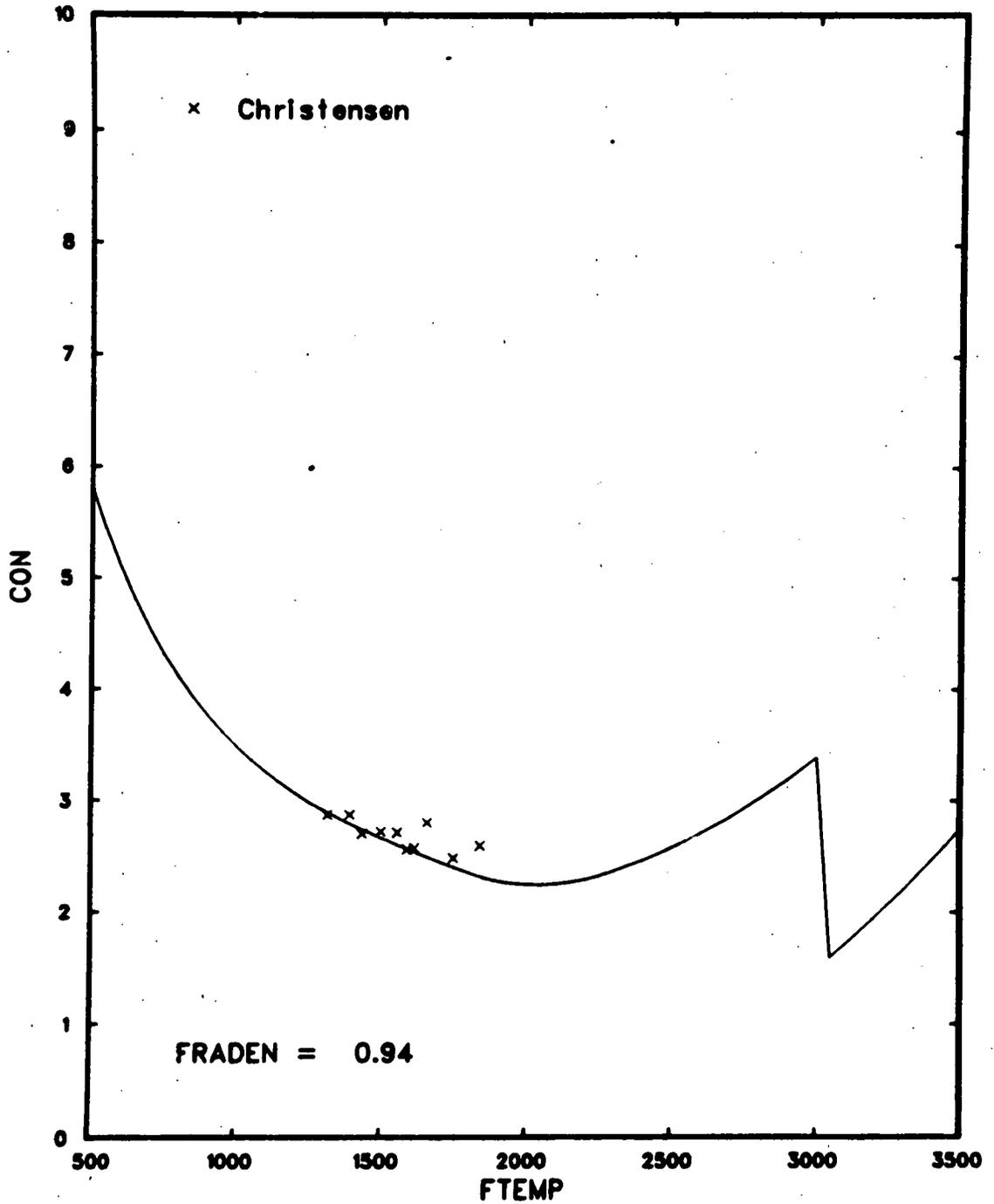


Fig. A-2.5 Model prediction for thermal conductivity of 0.94 of theoretical density  $UO_2$  compared to data from specimens with densities in the range .935 to 0.945 of theoretical density.

PLOT 7 11.23.48 TIME 1 FEB. 1979 JOB=HEATCON . IL DISPLA VER 7.3

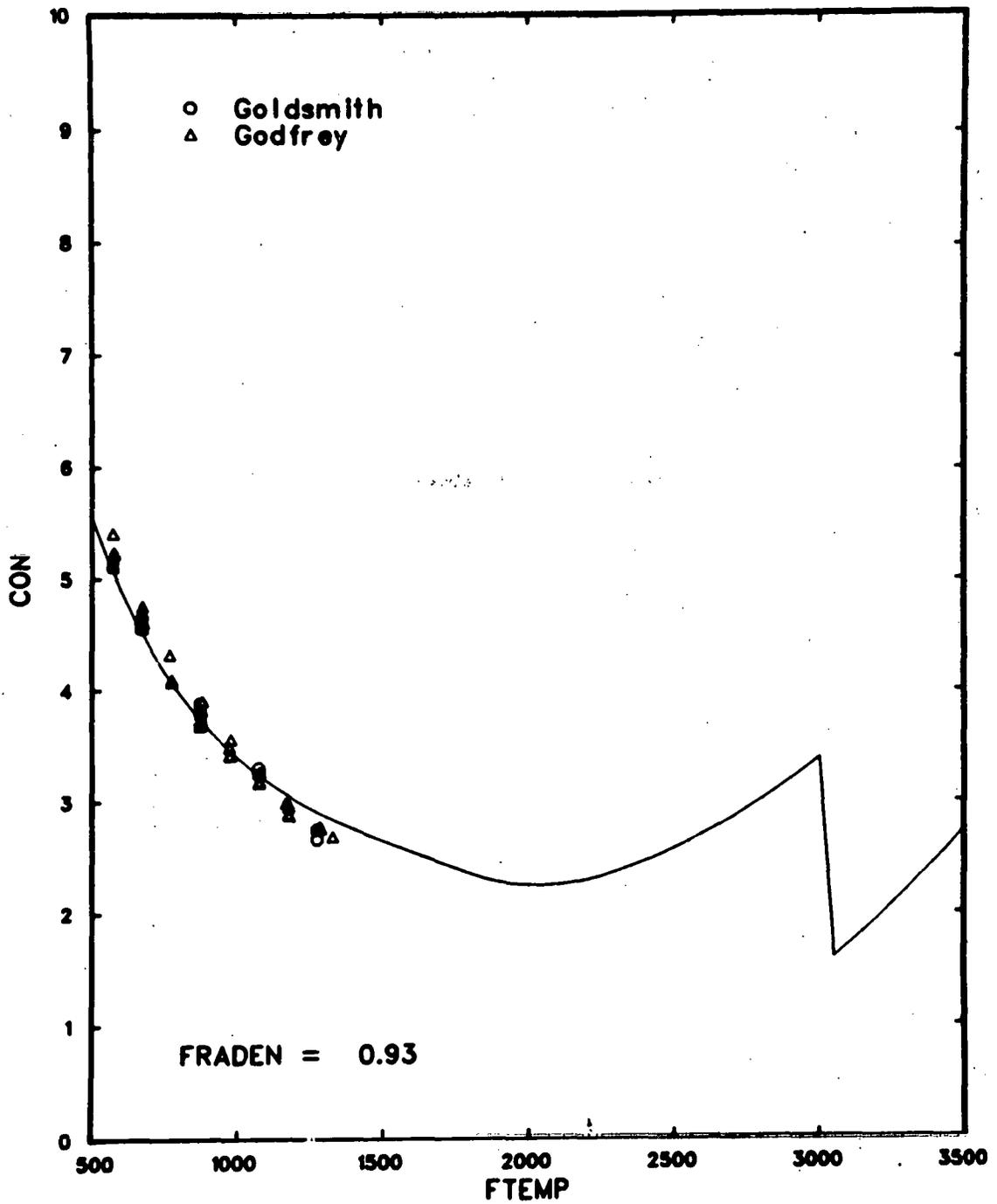


Fig. A-2.6 Model prediction for thermal conductivity of 0.93 of theoretical density  $UO_2$  compared to data from specimens with densities in the range 0.925 to 0.935 of theoretical density.

PLUJ 9 11.23.19 1700 1 FEB. 1979 J00-0000000 . IL DISPLA V03 7.3

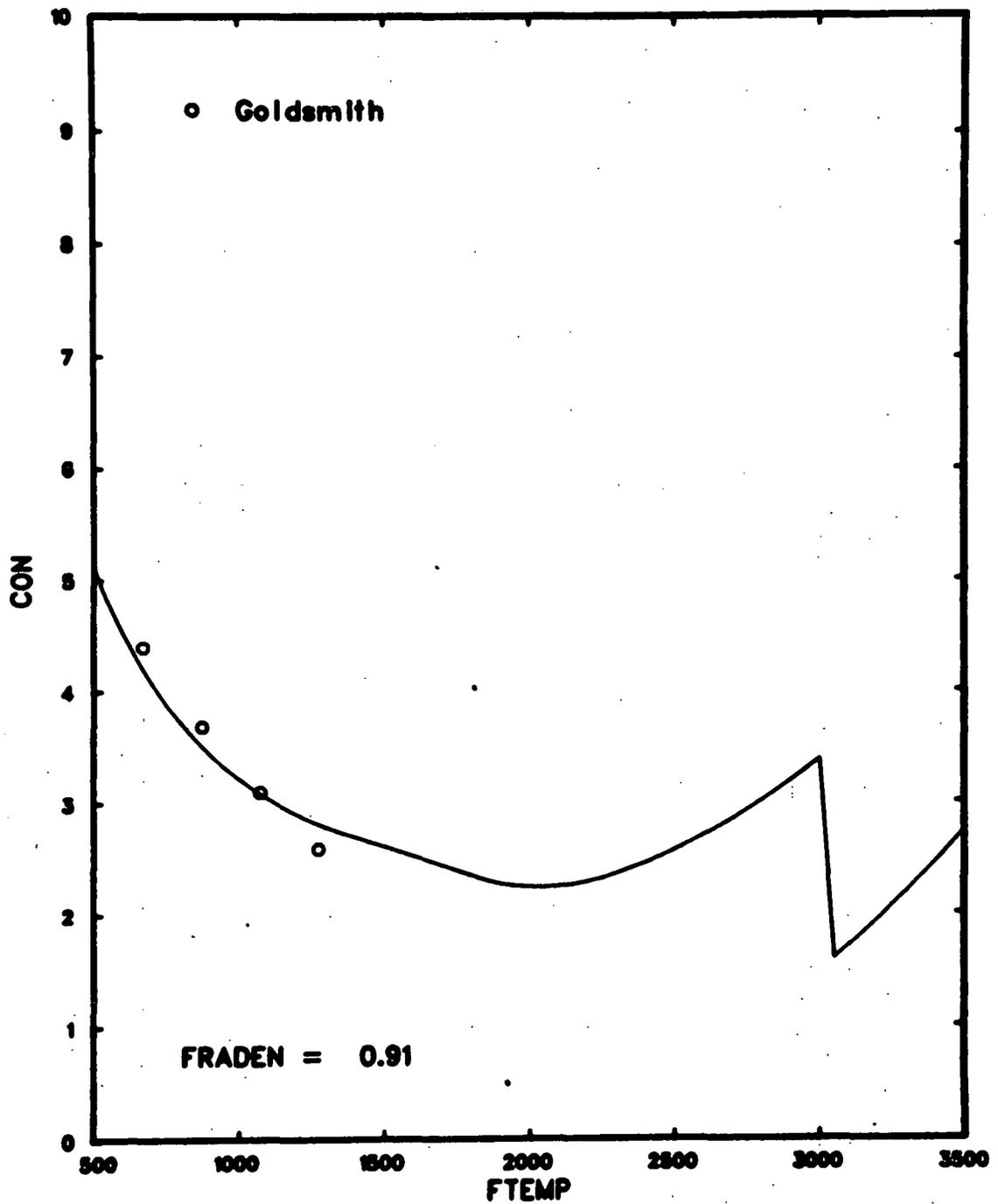


Fig. A-2.7 Model prediction for thermal conductivity of 0.91 of theoretical density  $UO_2$ , compared to data from specimens with densities in the range 0.905 to 0.915 of theoretical density.

PLU1 10 11.23.10 TIME 1 1723.1870 JOB=HEATCON . IL DISPLA FOR 7.3

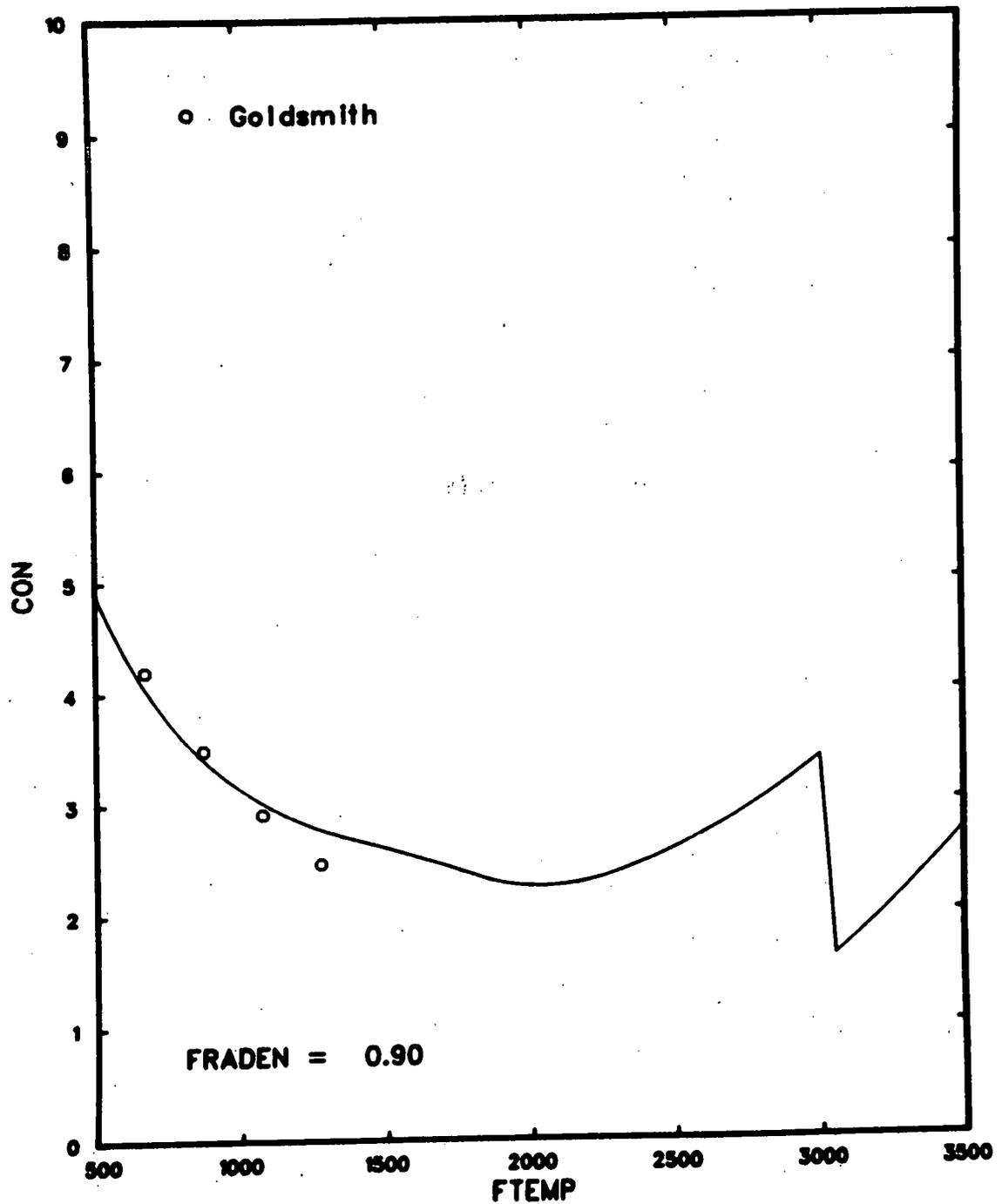


Fig. A-2.8 Model prediction for thermal conductivity of 0.89 of theoretical density  $UO_2$  compared to data from specimens with densities in the range 0.895 to 0.905 of theoretical density.

The  $UO_2$  data of each investigator show scatter which is nearly as large as the model standard error, an observation which strongly suggests that this part of the model is complete.

Mixed oxide data have not been compared to the current model because that part of the model is preliminary.

## 2.5 Fuel Thermal Conductivity Subcode FTHCON Listing and Comparison to the MATPRO-11 Version of the Subcode

A listing of the FTHCON subcode is given in Table A-2.IX. The expected standard error is computed within the subcode, but is not returned.

Figures A-2.9 and A-2.10 are computer generated plots which show the predicted thermal conductivity of  $UO_2$  fuel of 95 and 90% of the theoretical density. The solid lines were generated by the current subcode and the dashed lines were generated by the MATPRO-11 Version of the FTHCON code<sup>[A-2.35]</sup>. For 95% dense fuel the predicted low temperature conductivity is now approximately 0.3 W/(mK) higher than it was in the MATPRO-11 package. It is lower at temperatures above 2000 K. For 90% dense fuel, the predicted thermal conductivity has decreased slightly at low temperatures but increased by as much as 0.5 W/(mK) at temperatures near 1500 K. The predicted conductivity of liquid fuel has been substantially decreased in the new model.

TABLE A-2.IX

## LISTING OF THE FTHCON SUBCODE

```

SUBROUTINE FTHCON(FTEMP,FRADEN,FUTMTL,CON,DKDT)
C
C FTHCON CALCULATES THE FUEL THERMAL CONDUCTIVITY AND ITS
C DERIVATIVE WITH RESPECT TO TEMPERATURE AS A FUNCTION OF
C TEMPERATURE, DENSITY, OXYGEN TO METAL RATIO, COMPOSITION
C AND BURN UP
C
C CON = OUTPUT FUEL THERMAL CONDUCTIVITY (W/(M*K))
C DKDT = OUTPUT DERIVATIVE OF FUEL THERMAL CONDUCTIVITY
C WITH RESPECT TO TEMPERATURE (W/(M*K*K))
C
C FTEMP = INPUT FUEL TEMPERATURE (K)
C FRADEN = INPUT FUEL DENSITY (RATIO OF ACTUAL DENSITY TO
C THEORETICAL DENSITY)
C FUTMTL = INPUT OXYGEN TO METAL RATIO OF FUEL (ATOMS OXYGEN/
C ATOMS METAL)
C
C THE FOLLOWING INPUTS ARE BY COMMON BLOCK
C COMP = INPUT PUO2 CONTENT OF FUEL (PERCENT PUO2
C IN TOTAL FUEL WEIGHT)
C BU = INPUT BURNUP (MH-S/KG-U)
C EMFLAG(12) = INPUT SWITCH FOR EVALUATION MODEL. IF THIS
C VARIABLE IS EQUAL TO ON THE MATPRO MODEL FOR
C FUEL THERMAL CONDUCTIVITY IS REPLACED BY THE
C SUBCODE EMFTON
C
C THE FOLLOWING UNCERTAINTY IS COMPUTED BUT NOT RETURNED
C UCON = OUTPUT EXPECTED STANDARD ERROR OF THE FUEL
C THERMAL CONDUCTIVITY (W/(M*K))
C
C THE EQUATIONS USED IN THIS SUBROUTINE ARE BASED ON DATA FROM
C (1) J. A. CHRISTENSEN ET AL., URANIUM DIOXIDE THERMAL
C CONDUCTIVITY, TRANSACTIONS OF THE AMERICAN NUCLEAR
C SOCIETY 7 (1964) PP. 391 - 392
C (2) T. C. GODFREY ET AL., THERMAL CONDUCTIVITY OF
C URANIUM DIOXIDE AND ARMCO IRON BY AN IMPROVED
C HEAT FLUX TECHNIQUE, ORNL-3556 (1954)
C (3) J. L. BATES, HIGH TEMPERATURE THERMAL CONDUCTIVITY
C OF ROUND ROBIN URANIUM DIOXIDE, BNWL-1431 (1970)
C (4) R. L. GIBBY, THE EFFECT OF PLUTONIUM CONTENT ON THE
C THERMAL CONDUCTIVITY OF (U,PU)O2 SOLID SOLUTIONS,
C JOURNAL OF NUCLEAR MATERIALS 38 (1971) PP 163 - 177
C (5) J. C. WEILBACHER, DIFFUSIVITE THERMIQUE DE L'OXIDE
C D'URANIUM ET DE L'OXIDE DE THORIUM A HAUTE TEMPERATURE,
C HIGH TEMPERATURES - HIGH PRESSURE 4, (1972) PP 431 - 438
C (6) L. A. GOLDSMITH AND J. A. M. DOUGLAS, MEASUREMENTS
C THE THERMAL CONDUCTIVITY OF URANIUM DIOXIDE AT 670 -
C 1270 K, JOURNAL OF NUCLEAR MATERIALS 47, (1973) PP 31 - 42
C (7) I. C. HOBSON ET AL., EFFECT OF POROSITY AND STOICHIOMETRY
C ON THE THERMAL CONDUCTIVITY OF URANIUM DIOXIDE, JOURNAL
C OF PHYSICS SECTION D; APPLIED PHYSICS 7 (1974)
C PP 1003 - 1015
C (8) R. L. GIBBY, THE THERMAL DIFFUSIVITY AND THERMAL
C CONDUCTIVITY OF STOICHIOMETRIC (UO.8,PUO.2)O2, BNWL-704
C (1968)
C (9) R. L. GIBBY, THE EFFECT OF OXYGEN STOICHIOMETRY ON THE
C THERMAL DIFFUSIVITY AND CONDUCTIVITY OF (UO.75,PUO.25)
C O2-X BNWL-927 (1969)
C (10) L. A. GOLDSMITH AND J. A. M. DOUGLAS, THE THERMAL
C CONDUCTIVITY OF PLUTONIUM-URANIUM DIOXIDE AT
C TEMPERATURES UP TO 1373 K, JOURNAL OF NUCLEAR MATERIALS
C 43 (1972) PP 225 - 233

```

TABLE A-2.IX (cont...)

LISTING OF THE FTHCON SUBCODE

C (11) H. E. SCHMIDT, DIE WAERMELEITFAEHIGKEIT VON URAN AND  
 C URAN-PLUTINIUM DIOXYD BEI HOHEN TEMPERATURES, FORSCHUNG  
 C INGENIEUR-WEISEN 38 (1976) PP 149 - 151  
 C (12) D. R. GLANDER, FUNDAMENTAL ASPECTS OF NUCLEAR REACTOR  
 C FUEL ELEMENTS, TID-26711-P1 (1976)

C FTHCON WAS ORIGINALLY CODED BY C. S. OLSEN FEB 1975  
 C MODIFIED BY G. A. REYMANN AUGUST 1978  
 C MODIFIED BY D. L. HAGMAN JANUARY 1979

C COMMON /PHYPRO / FTMELT, FHEFUS, CTMELT, CHEFUS, CTRANB,  
 C CIRANE, CTRANZ, FDELTA, BU ,COMP

C COMMON /LACHOL/ MAXIDX, EMFLAG  
 C DIMENSION EMFLAG(1)  
 C DIMENSION L(2)  
 C DATA ON / ZHON /  
 C # OFF / SHUFF /  
 C # LOCIDX / 12 /

C FIND CONSTANTS

C FRPU = COMP/100.  
 C A = 0.339 + 12.6 \* ABS( 2.0 - FDMIL )  
 C IF(FRPU .GT. 0.75) FRPU = 0.75  
 C B = 6.867E-02 \* ( 1.0 + 0.6238 \* FRPU )  
 C T = FTEMP  
 C I = 1

C FIND SPECIFIC HEAT AT CONST. VOL. AND VOLUME CHANGE

C 10 TR = 535.265/T  
 C CV = 296.7 \* TR \* TR \* EXP(TR) / ( ( EXP(TR) - 1.0)\*\*2 )  
 C DV = 1.0 + 3.0 \* ( 1.0E-05 \* T - 3.0E-03 + 4.0E-02 \*  
 C # EXP(-5.0E+03/T) )  
 C IF(FRPU .LT. 0.0001) GO TO 20  
 C USE RULE OF MIXTURES FOR MIXED OXIDES  
 C TR = 571.0/T  
 C CV = CV \* ( 1.0 - FRPU ) + ( 347.4 \* TR \* TR \* EXP(TR) /  
 C # ( ( EXP(TR) - 1.0 )\*\*2 ) ) \* FRPU  
 C DV = ( DV - 1.0 ) \* ( 1.0 - FRPU ) + 3.0 \* ( 9.0E-06 \* T  
 C # - 2.7E-03 + 7.0E-02 \* EXP(-5.072E+03/T) ) \* FRPU + 1.0

C FIND POROSITY CORRECTION

C 20 BETA = 6.50 - 4.09E-03 \* T  
 C IF(T .GE. 1364.647) BETA = 15.811308 - T \* ( 0.01833647 - T \* 5.E-6 )  
 C IF(T .GT. 1833.647) BETA = -1.0

C FIND ELECTRONIC CONTRIBUTION

C CGNE = ( 5.2997E-03 \* T \* EXP(-13358.0/T) ) \*

TABLE A-2.IX (cont...)

LISTING OF THE FTHCON SUBCODE

```

#      (1.0 + 0.169 * ((13358.0/ T      + 2.0)**2  ) )
BTEMP = T
IF (T .GE. 1800.) BTEMP = -3240. + T * (4.6 - T * 0.001)
IF (T .GE. 2300.) BTEMP = 2050.
C
C      FIND CONDUCTIVITY
C
C      C(I) = (CV * FRADEN) / (DV * (A + B * BTEMP ) *
#      (1.0 + BETA * (1.0 - ERADEN) ) ) + CONE
IF (FTEMP .GE. FTMELT) C(I) = CONE
C
C      FIND DERIVATIVE OF FUEL CONDUCTIVITY
C
C      I = I + 1
T = FTEMP + ((-1.0)**I)
IF (I .LT. 3) GO TO 10
CON = C(I)
DKDI = (C(I) - C(I-1))
C
C      FIND UNCERTAINTY
C
UCON = (0.2 * (1.0 - FRPU) + 0.7 * FRPU ) * (1.0 + ABS(2.0 - FOTML
# ) * 10.)
IF (FTEMP .GE. FTMELT) UCON = C(I) / 2.0
IF (EMFLAG(LCLOX) .EQ. ON) CON = FMFION(FTEMP,FRADEN,FTMELT)
RETURN
END

```

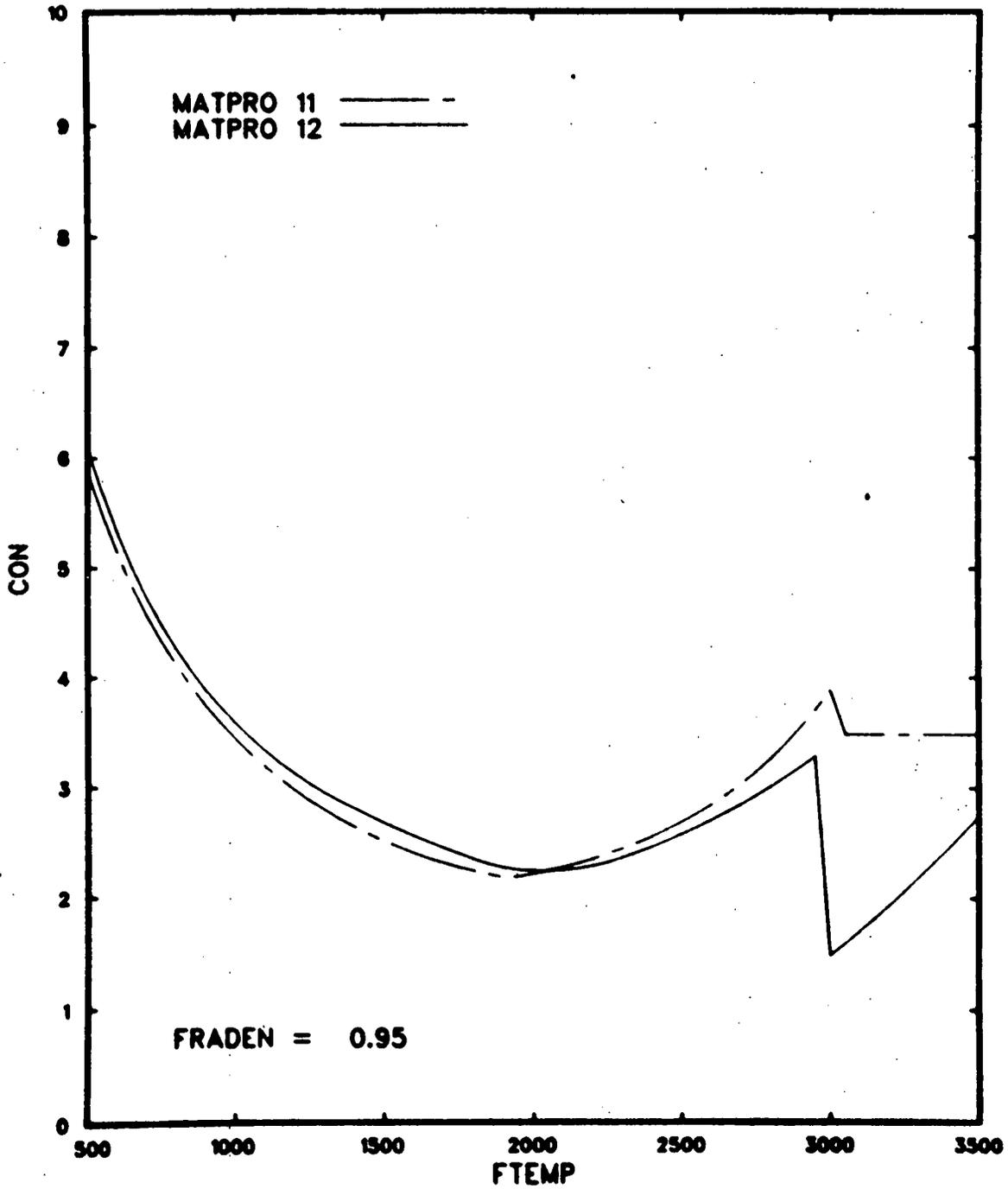


Fig. A-2.9 Comparison of thermal conductivity predicted by the MATPRO-11 version of FTHCON to the conductivity returned by the current subcode for 0.95 of theoretical density  $UO_2$

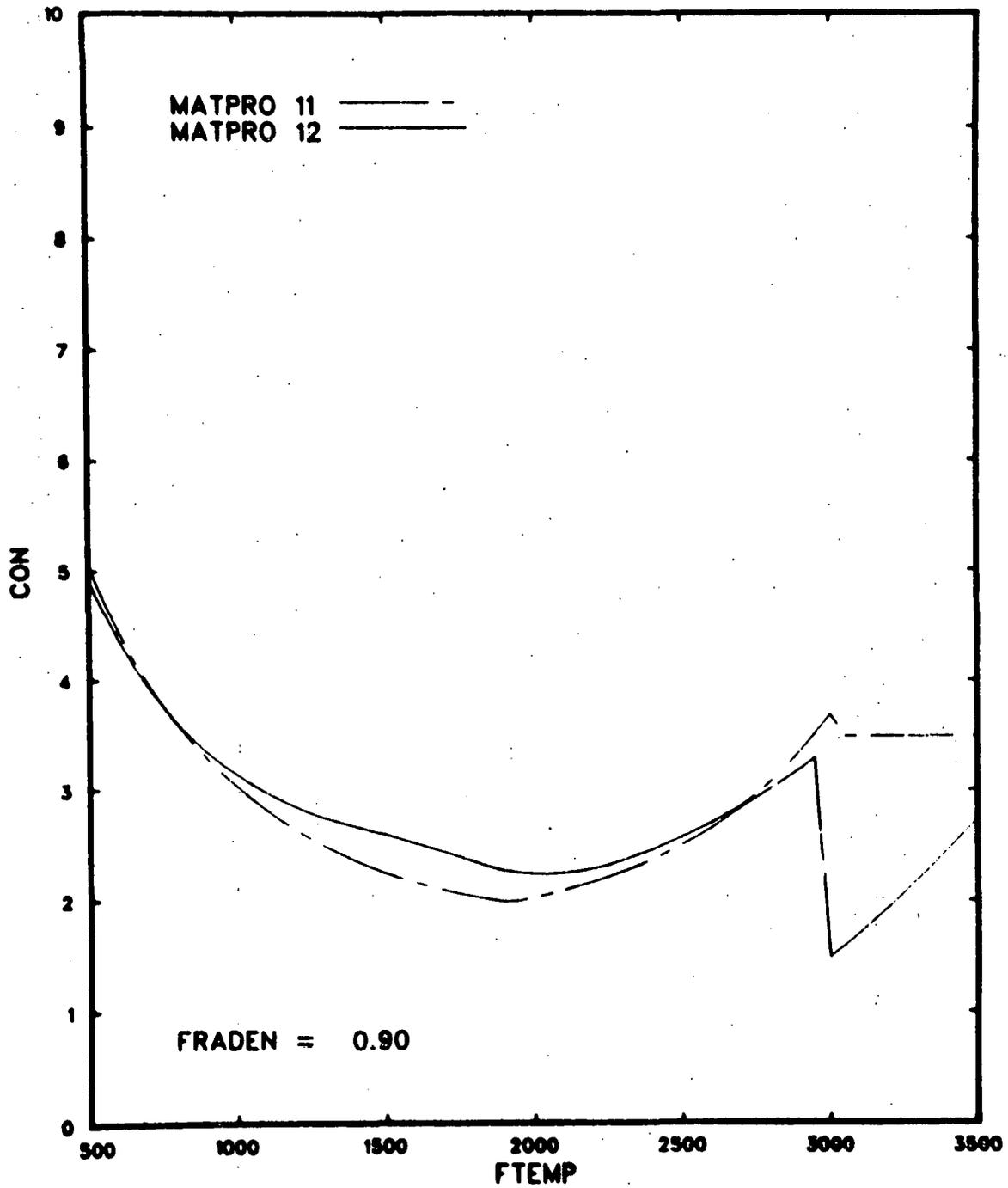


Fig. A-2.10 Comparison of thermal conductivity predicted by the MATPRO-11 version of FTHCON to the conductivity returned by the current subcode for 0.90 of theoretical density  $UO_2$ .

## 2.6 References

- A-2.1. D. R. Olander, Fundamental Aspects of Nuclear Reactor Fuel Elements, TID-26711-P1 (1976).
- A-2.2. C. Kittel, Introduction to Solid State Physics, John Wiley & Sons, Inc., (1956).
- A-2.3. R. Berman, Thermal Conduction in Solids, Clarendon Press, Oxford, (1976).
- A-2.4. H. J. Goldsmid, The Thermal Properties of Solids, Dover Publications, Inc., New York, (1965).
- A-2.5. J. L. Bates, C. A. Hinman and T. Kawada, "Electrical Conductivity of Uranium Dioxide", Journal of the American Ceramic Society, 50 pp. 652-656 (1967).
- A-2.6. G. P. Marino, "The Porosity Correction Factor for the Thermal Conductivity of Ceramic Fuels", Journal of Nuclear Materials, 38 (1970) pp 178-190.
- A-2.7. A. L. Loeb, "Thermal Conductivity: A Theory of Thermal Conductivity of Porous Materials," Journal of the American Ceramic Society, 37 (1954) pp 96-99.
- A-2.8. J. R. MacEwan, R. L. Stoute, and M. F. Notley, "Effect of Porosity of the Thermal Conductivity of  $UO_2$ ," Journal of Nuclear Materials, 24 (1967) pp 109-112.
- A-2.9. A. Biancheria, "The Effect of Porosity on Thermal Conductivity of Ceramic Bodies," Transactions of the American Nuclear Society, 9 (1966) p 15.
- A-2.10. G. Ondracek and B. Schulz, "The Porosity Dependence of the Thermal Conductivity for Nuclear Fuels," Journal of Nuclear Materials, 46 (1973) pp 253-258.
- A-2.11. J. C. VanCraeynest and J. P. Stora, "Effect de la Porosite sur la Variation de Conductibilite Thermique du Bioxyde d'Uranium en Fonction de la Temperature," Journal of Nuclear Materials, 37 (1970) pp 153-158.
- A-2.12. L. A. Goldsmith and J. A. M. Douglas, "Measurements of the Thermal Conductivity of Uranium Dioxide at 670-1270 K," Journal of Nuclear Materials, 47 (1973) pp 31-42.
- A-2.13. I. C. Hobson, R. Taylor, and J. B. Ainscough, "Effect of Porosity and Stoichmetry on the Thermal Conductivity of Uranium Dioxide," Journal of Physics Section D: Applied Physics, 7 (1974) pp 1003-1015.
- A-2.14. R. R. Asamoto, F. L. Anselin, and A. E. Conti, "The Effect of Density on the Thermal Conductivity of Uranium Dioxide," Journal of Nuclear Materials, 29 (1969) pp 67-81.

- A-2.15. J. C. Hedge, Measurement of Thermal Conductivity of Uranium Oxide, AECU-3881, Armour Research Foundation of Illinois Institute of Technology (September 20, 1956).
- A-2.16. W. D. Kingery et al, "Thermal Conductivity X: Data for Several Pure Oxide Materials Corrected to Zero Porosity," Journal of the American Ceramic Society, 37 (1954) pp 107-110.
- A-2.17. F. J. Hetzler et al, The Thermal Conductivity of Uranium and Uranium-Plutonium Oxides, GEAP-4879 (August 1967).
- A-2.18. T. G. Godfrey et al, Thermal Conductivity of Uranium Dioxide and Armco Iron by an Improved Radial Heat Flow Technique, ORNL-3556 (June 1964).
- A-2.19. J. Lambert Bates, High Temperature Thermal Conductivity of "Round Robin" Uranium Dioxide, BNWL-1431 (July 1970).
- A-2.20. C. F. Lucks and H. W. Deem, "Thermal Conductivity and Electrical Conductivity of  $UO_2$ ," Progress Relating to Civilian Applications During June 1960, BMI, 1448 (July 1, 1960).
- A-2.21. J. A. Christensen et al, "Uranium Dioxide Thermal Conductivity," Transactions of the American Nuclear Society, 7 (1964) pp 391-392.
- A-2.22. M. F. Lyons et al,  $UO_2$  Pellet Thermal Conductivity from Irradiations with Central Melting, GEAP-4624 (July 1964).
- A-2.23. R. D. Reiswig, "Thermal Conductivity of  $UO_2$  to 2,100°C," Journal of the American Ceramic Society, 44 (1961) pp 48-49.
- A-2.24. J. Stora et al, Thermal Conductivity of Sintered Uranium Oxide Under In-Pile Conditions, EURAEC 1095 (CEA-R 2585) (August 1964).
- A-2.25. C. Ferro, C. Patimo, and C. Piconi, "Thermal Diffusivity of Mixed ( $Th_x U_{1-x}$ ) Oxides and Some Materials to be Used as Reference in the Range 650-2,700 K," Journal of Nuclear Materials, 43 (1972) pp 273-276.
- A-2.26. J. C. Weilbacher, "Diffusivité Thermique de l'oxyde d'Uranium et de l'Oxyde de Thorium à Haute Temperature," High Temperatures-High Pressure, 4 (1972) pp 431-438.
- A-2.27. R. L. Gibby, "The Effect of Plutonium Content on the Thermal Conductivity of  $(U,Pu)O_2$  Solid Solutions," Journal of Nuclear Materials, 38 (1971) pp 163-177.
- A-2.28. R. L. Gibby, The Thermal Diffusivity and Thermal Conductivity of Stoichiometric  $(U_{0.8}Pu_{0.2})O_2$ , BNWL-704 (May 1968).

- A-2.29. R. L. Gibby, The Effect of Oxygen Stoichiometry on the Thermal Diffusivity and Conductivity of  $U_{0.75}Pu_{0.25}O_{2-x}$  BNWL-927 (January 1969).
- A-2.30. L. A. Goldsmith and J. A. M. Douglas, "The Thermal Conductivity of Plutonium-Uranium Dioxide at Temperatures up to 1,273 K," Journal of Nuclear Materials, 43 (1972) pp 225-233.
- A-2.31. M. Serizawa et al, "Thermal Diffusivity and Thermal Conductivity of Uranium-Plutonium Dioxide," Journal of Nuclear Materials, 34 (1970) pp 224-226.
- A-2.32. J. C. Van Craeynest and J. C. Weilbacher, "Etude de la Conductibility Thermique des Oxides Mixed d'Uranium et de Plutonium," Journal Of Nuclear Materials, 26 (1968) pp 132-136.
- A-2.33. H. E. Schmidt, "Die Waermeleitfaehigkeit von Uran and Uran-Plutonium Dioxyd bei Hohen Temperaturen," Forshucng, Ingenieur-Wesen, 38 (1972) pp 149-151.
- A-2.34. H. E. Schimdt, "Die Waermeleitfaehigkeit von Uran and Uran-Plutonium Dioxyd bei Hohen Temperaturen," High Temperatures-High Pressure, 3 (1971) p 345.
- A-2.35. D. L. Hagrman and G. A. Reymann, MATPRO Version 11. A Handbook of Materials Properties for Use in the Analysis of Light Water Reactor Fuel Rod Behavior, TREE-1280, NUREG/CR-0497 (to be published, February, 1979).