**An In-Pile Testing Program
to Study the
Performance Characteristics
of Coated Particle Fuels***

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Steven A. Wright
Sandia National Laboratories
Albuquerque, NM 87185
(505) 845-3014

ABSTRACT

Sandia National Laboratories is actively involved in testing coated particle nuclear fuels for the Space Nuclear Thermal Propulsion (SNTTP) program managed by Phillips Laboratory. The testing program integrates the results of numerous in-pile and out-of-pile tests with modeling efforts to qualify fuel and fuel elements for the SNTTP program. This paper briefly describes the capabilities of the Annular Core Research Reactor (in which the experiments are performed), the major in-pile tests, and the models used to determine the performance characteristics of the fuel and fuel elements.

INTRODUCTION

Sandia National Laboratories (SNL) is actively involved in testing coated particle nuclear fuels for space propulsion applications. The Annular Core Research Reactor (ACRR) is the major tool used for nuclear testing, and complete hot cell capabilities are available for rapid posttest examinations of the irradiated fuel. These experiments combined with numerous out-of-pile furnace tests and modeling efforts are the major components of the fuels development task at SNL. This effort is being performed for the Space Nuclear Thermal Propulsion (SNTTP) program managed by the Phillips Laboratory (USAF).

Sandia has broad experience in performing in-pile irradiation experiments. Over 100 experiments have been performed in the last decade. Recently, numerous in-pile experiments have been performed to study the operational characteristics of coated particle carbide fuels and particle bed fuel elements for the Multi-Mega Watt and SNTTP programs. Many new experiments are currently in progress or are planned for the SNTTP program. These new experiments will continue to evaluate the performance characteristics of fuel particles and particle bed fuel elements. The results will provide safety-related information such as fission product release

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characteristics, failure mechanisms during normal operating conditions, and will address severe accident safety issues.

A major portion of the testing program is to verify and validate mechanistic models of fuel and fuel element behavior using the results of the experiments. Currently, no existing facility is capable of testing fuel and fuel elements to the demanding DOE requirements of high power densities, temperatures, and operating times. As such, it will be necessary to perform experiments that selectively explore operating behavior over a subset of the desired operating envelope and use codes and models (which have been validated by the experiments) to extrapolate to operating regimes currently unobtainable with existing facilities. In addition, codes of this type will be essential in the licensing and safety assessment of a national facility capable of groundtesting DOE or SEI fuel elements and engines.

As part of the SNTP fuels testing program within Sandia National Labs, a suite of integrated computer codes is being developed. These codes, though still in the development phase, are currently operational and are capable of mechanistically modeling either the details of the fuel particles or the fuel element during normal and off-normal operating conditions. The codes include a fuel particle performance code and a two-dimensional thermal-hydraulics code capable of modeling flow in porous media with internal heating.^{1,2}

ACRR TESTING CAPABILITIES

The ACRR is a BeO-UO₂ fueled Triga-like reactor. Figure 1 shows a top view of the reactor. The reactor has two cavities available for irradiation. The main cavity, located in the center of the annular core, is 23 cm in diameter. The surrounding BeO-UO₂ elements have an active fuel height of 52 cm. The other cavity is a ZrH-UO₂ fueled subcritical assembly located adjacent to the ACRR. The subcritical assembly is driven by the main reactor, and its geometry may be changed to suit the experiment. This cavity is currently cylindrical and has a 55.8 cm diameter. Because of the higher flux levels, the ACRR central cavity is the primary irradiation site used for SNTP program testing.

Operating Modes of the ACRR

The operating modes of the reactor are very flexible. The control rod drive mechanisms are capable of three modes of operation: (1) steady-state operations, (2) programmed power transients, and (3) pulsed operations. These modes of operation conveniently span the space nuclear propulsion run times or power levels as required by DOE or SEI missions during normal operations and for accident condition studies.

ACRR steady-state operations allow small volumes of fuel (a few cm³) to be irradiated for hours to days at power density levels up to 1 MW/l in small test beds. These types of irradiations are frequently used for special effects tests on small beds

containing several tens of thousands of fuel particles. Some of the more important results of the special effects tests include failure mechanism identification, failure fraction determination, and fission product release measurements.

The programmed power transient operations are used to irradiate Particle Bed Reactor fuel elements to 1-6 MW/l for tens of seconds to a few seconds. Fuel elements lengths may vary from 0.1 m up to .75 m depending on the objective of the test. Smaller volumes of fuel can be irradiated to 5-60 MW/l during these programmed power transients. Figure 2 illustrates an abbreviated programmed power transient capable of heating a PBR fuel element to 1.5 MW/l. Ongoing modifications to the control rod drive mechanisms will allow a 50% improvement in the capabilities of the programmed power transients of the ACRR. These modifications are scheduled for availability in early FY93.

Pulsed operations are useful for safety studies. Typical ACRR pulsed power transients can irradiate small volumes of fuel (a few cm³) up to power densities of 6000 MW/l for 10 ms. These types of transients allow one to study severe accidents such as unplanned reactivity insertion transients.

ACRR Experiment Review and Approval Process

SNL has an internal independent review and approval system for the safety analysis of reactor experiments. This process allows for internal safety evaluation and approval of experiments within the broad range of ACRR operating conditions. Experiments that exceed the umbrella of operation as outlined in the ACRR Safety Analysis Report³ can be performed with review and approval by DOE.

Unique features of In-Pile Testing

Unique features of space reactor fueled experiments that have been or are being performed in the reactor include:

1. heating fuel (either in small particle beds or fuel elements) to temperatures exceeding 3000 K,
2. high power irradiation, and fuel element cooling using high pressure hydrogen cooling loops that are capable of providing cryogenic inlet coolant temperatures,
3. high speed cinematography and video photography during the reactor transients,
4. development and verification of computer-controlled algorithms to investigate autonomous computer control of the reactor and to study startup and shutdown transient effects on the fuel particles and the fuel elements, and

5. real time optical pyrometry (single and two color).

CURRENT OR PLANNED IN-PILE TESTS

Particle Nuclear Tests (PNT)

The Particle Nuclear Tests (PNT) are a series of experiments that have been performed for the SNTP program.⁴ More than 200,000 fuel particles have been irradiated in 12 fuel beds at temperatures ranging from 1800 K to over 3000 K. Figure 3 shows a schematic of the capsule and fuel holder used to irradiate the particle beds. These experiments have been useful in quantifying the performance limiting features of the fuel and in determining effective fission product release diffusion coefficients for isotopes of Te, and I. The experiments have also quantified Xe fission gas release dependence on failed fuel fractions.

Nuclear Element Tests

A series of Nuclear Element Tests (NET) are currently in process to provide engineering validation and demonstration of fuel element related technologies, and to develop a database of experimental information to support analytical design methods for the SNTP program.⁵ A unique feature of these experiments is that the fuel elements are cooled by a high pressure, cryogenic hydrogen loop. Figure 4 shows a schematic of the NET capsule. The NET experiments will irradiate fuel elements for many cycles to prototypic mixed mean exit temperatures at power densities of a few MW/l for tens of seconds. Much higher power densities can be achieved for short start-up transient studies if required. Total time at temperature will approach mission requirements during the longer lower power density experiments.

Severe Accident Tests

Pulsed operations are useful for safety studies. These types of transients can study severe accidents such as those caused by unplanned reactivity insertion transients. Typical ACRR pulsed power transients can irradiate small volumes of fuel (cc's) up to 6000 MW/l for 10 ms. These power levels will cause rapid vaporization of the fuel and pressurization of the fuel volume. Proposed experiments will use these types of transient heating operations to support hypothetical core disruptive accident modeling. The interaction between the experiments and the modeling will provide the necessary validation effort to determine the realistic pressurization potential and fuel dispersal rates for these types of accidents.

MODELING

Code development teams work closely with the experiment teams to assure realism of the models, to interpret the experimental results, and to verify the codes. The modeling teams frequently point out critical uncertainties in the analysis, which in turn places requirements for special effects experiments to address the uncertainty. The codes are used to improve the fuel particle or fuel element designs with goals of increasing safety margins or avoiding deleterious materials effects.

Fuel Particle Code

A computer code is being developed to predict fuel performance and fission product release from coated fuel particles. The code development is intended to provide a tool to evaluate operational safety of various fuel particle designs and to provide experiment analysis capability. The code includes routines for calculation of fission product decay chains (including relatively short-lived isotopes not usually included in power reactor codes), release of fission products from intact and failed particles, the temperature profile in a particle, stress-strain with creep and plasticity effects, grain growth, dissolution of the coating by molten fuel, mechanical fuel failure, and particle failure fraction (for brittle and chemical attack failure modes). Provisions are also made for geometry changes occurring as a result of fuel kernel melt, and coating failure.

Particle Bed Thermal-Hydraulics Code

F2D² is a general, two-dimensional, fully compressible, thermal-hydraulics code written to model the detailed fluid dynamics effects of particle bed fuel elements and other experimental environments that have coupled heat transfer and fluid flow. A variety of boundary conditions have been included so that the experimental system behavior can be coupled to the fluid flow. The coordinate system can be either cartesian or cylindrical, and conventional staggered grid formalism is used. The code solves two energy equations, one for gas and the other for structure, which makes the code capable of solving porous media flow problems with internal heat generation. The code is currently being used to study multidimensional thermal hydraulic effects for the NET experiments.

POSTTEST EXAMINATIONS

After irradiation of space reactor fuels, the SNL Hot Cell Facility capabilities are used to examine the behavior of the fuel and fuel elements. Typical analyses include optical and scanning electron microscope photos of polished cross sections and whole fuel particles. Optical magnifications up to 500 X are typically achieved, and SEM magnifications up to 5000 X are routine. Other analyses include energy and wavelength dispersive analyses, Raman spectroscopy, and fracture strength testing capabilities. These analytical tools are used to determine the performance limits of fuel and fuel elements.

The experiments and posttest analyses have revealed that the performance limits are below the ultimate melt (or eutectic) temperature of the coating materials. These limits are influenced by solid-state thermal chemical and mechanical effects as well as by fabrication methods and process control variables. Typical limiting conditions can be caused by impurity concentration, thermal creep, grain growth, porosity agglomeration, defect distributions, residual stresses, stoichiometry changes, and other mechanisms.⁶ Crush test measurements clearly indicate that crush strength is highly correlated to grain size. This has important ramifications for operational safety since the fraction of fuel that fails due to stress induced brittle fracture is dependent on the grain size and defect distribution. The fuel failure significantly affects the magnitude of fission product releases and the likelihood for failure propagation.

SUMMARY

In-pile experiments performed in the ACRR are valuable tools for determining the operational characteristics and performance limits of fuel and fuel elements currently being proposed for space propulsion. Numerous in-pile experiments have already been performed on space reactor fuels. Posttest examination and analyses data from these experiments are influencing the fabrication and design of both coated fuel particles and fuel elements. In addition, mechanistic models are being developed to extend predictive capabilities into operating regimes unobtainable with currently available test facilities.

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