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THE USE OF FILLER MATERIALS TO AID
SPENT NUCLEAR FUEL DRY STORAGE

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ABSTRACT

The use of filler materials (also known as stabilizer or encapsulating materials) was investigated in conjunction with the dry storage of irradiated light water reactor (LWR) fuel. The results of this investigation appear to be equally valid for the wet storage of fuel. The need for encapsulation and suitable techniques for closing was also investigated. Various materials were reviewed (including solids, liquids, and gases) which were assumed to fill the void areas within a storage can containing either intact or disassembled spent fuel. Materials were reviewed and compared on the basis of cost, thermal characteristics, and overall suitability in the proposed environment. A thermal analysis was conducted to yield maximum centerline and surface temperatures of a design basis fuel encapsulated within various filler materials.

In general, air was found to be the most likely choice as a filler material for the dry storage of spent fuel. The choice of any other filler material would probably be based on a desire, or need, to maximize specific selection criteria, such as surface temperatures, criticality safety, or confinement.

ACRONYMS

AFR	Away-From-Reactor
AGNS	Allied-General Nuclear Services
BNFP	Barnwell Nuclear Fuel Plant
BWR	Boiling Water Reactor
LWR	Light Water Reactor
PWR	Pressurized Water Reactor
MWd	Megawatt-day
MTU	Metric Tons of Uranium

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1.0 INTRODUCTION AND SUMMARY

Studies previously conducted by Allied-General Nuclear Services (AGNS) have addressed converting the Barnwell Nuclear Fuel Plant (BNFP) to an Away-From-Reactor (AFR) underwater storage facility⁽¹⁾ or also to an AFR dry storage facility.⁽²⁾ This report analyzes the use of alternative filler materials such as water, lead shot, steel, sand, air, etc., which could be used to encapsulate spent nuclear fuel within a canister. The encapsulated fuel could subsequently be stored in a wet or dry storage facility which could be at an AFR site or a utility reactor site. The spent fuel, itself, could either be left intact (an entire PWR or BWR assembly per storage canister) or disassembled (two assemblies per storage canister).

It was assumed that the filled canisters would be stored for an interim period of time, say 10 to 30 years. The stored fuel would then be sent to either a reprocessing facility or to a federal repository.

The purpose of this study was to determine if encapsulation of spent fuel with a filler material is desirable, compare some alternative filler materials (physical and economic characteristics), and to review some appropriate means to seal the storage canisters if filler materials are used.

For the dry storage of spent fuel, it appears (see Tables 6 and 7 of the Appendix) that air is the best filler media. The use of filler materials other than air for dry storage of spent fuel could only be justified if a specific end result, e.g., containment or criticality control was deemed very important.

2.0 METHODOLOGY

The objective of this study was to determine the need for encapsulation, evaluate the desirability of the use of fillers, and review suitable techniques for closing the fuel container. The major emphasis was placed upon the review of filler materials. The following steps were performed to accomplish this objective:

- (1) A literature search was performed to gather information concerning the use of filler materials for the dry storage of the LWR fuel.
- (2) Criteria and design bases were established.
- (3) The need for encapsulation was reviewed.
- (4) Possible filler materials were selected including solids, liquids, and gases.
- (5) A consultant, Ridihalgh, Eggers & Associates, Inc., knowledgeable in thermal analysis was selected.
- (6) Computer analyses were performed to determine the effect of filler materials on centerline and surface temperatures of design bases fuel stored in containers.
- (7) Costs and overall suitability (corrosion resistance, radiation tolerance, etc.) were compiled and compared for the candidate filler materials.
- (8) This report was written documenting the findings of the use of filler materials to aid spent fuel dry storage.

3.0 DESIGN BASES

The LWR spent fuel characteristics used in the filler material thermal analysis were based on a Westinghouse 17x17 PWR spent fuel that had been cooled for five years since removal from a reactor core. Furthermore, the design basis fuel was assumed to have initial enrichment of 4.1%, a burnup of 33,000 MWd/MTU, and a specific power output of 35 MW/MTU.

Spent fuel storage canisters were assumed to be orientated vertically and in an environment (wet or dry) of 180°F maximum (82°C). The fuel cladding was assumed to be Zircaloy. The stored fuel, within an approximately 9-1/4-inch square container, would consist of one intact fuel assembly or two disassembled fuel assemblies. The filler material was assumed to fill all void areas in the container not occupied by the stored fuel.

Various researchers in the past (e.g., Reference 5 of the Appendix) have warned against storing fuel in modes that allow centerline temperatures to exceed about 380°C. Degradation of fuel and cladding could possibly result at relatively high temperatures. Therefore, the maximum centerline temperature of interest was selected at 380°C (716°F). Materials that insulated the fuel and raised the fuel temperature to above 380°C were viewed as detrimental and eliminated from further study as possible filler materials.

The thermal analysis was performed with mathematical models of PWR fuel assemblies utilizing the TRUMP (Reference 3 of the Appendix) heat transfer computer program. Results of standard heat transfer correlations were used as input into the TRUMP program.

For an intact or disassembled PWR fuel assembly, the fuel rod diameter was assumed to be 0.374 inches. The center-to-center pin spacing for an intact fuel assembly was assumed to be 0.496 inches. For disassembled fuel, a square lattice arrangement was assumed resulting in a center-to-center spacing of 0.374 inches (assumes pin-to-pin contact).

4.0 DISCUSSION

The disposition of spent LWR fuel has been under review, particularly during the past four or five years. Some have argued for a "throwaway" fuel cycle, others argue for reprocessing, while still others call for interim storage.

The purpose of this paper is to review the use of filler materials to encapsulate LWR spent fuel during interim storage. The storage environment may be either wet (pools) or dry (vaults, caissons, etc.). The fuel may be subsequently sent to either a federal repository ("throwaway" fuel cycle) or to a reprocessing facility (reprocessing fuel cycle).

4.1 Advantages and Disadvantages of Containment and Encapsulation

There are several reasons for placing the intact fuel assemblies within fuel storage containers. These reasons include: (1) the fuel could drop off particles of radioactive crud, cladding, or even fuel and they would still remain secure within the container and would not contaminate the storage area, (2) from an accountability standpoint, each container can be identified easier from permanent markings made on each container, (3) from a safeguards standpoint, each container may be individually capped and a tamper-proof seal or lock may be attached, (4) the racks could be less expensive to fabricate since they may be simply support brackets made from angle iron, pipes, etc., (5) the storage container may meet the qualifications to be classified as a containment barrier and, therefore, the fuel would be one step closer to permanent disposal during interim storage, (6) from an operations standpoint, there would be a maximum of two sizes of storage containers (BWR and PWR) compared with various widths and lengths of fuel assemblies, (7) a fuel assembly encased in the proposed storage container would be able to better survive accident scenarios involving impacts and rough handling. It is not known, at this time, whether the use of individual containers would be beneficial from a seismic standpoint.

Another advantage to containment, is that it allows the use of filler materials to encapsulate the spent fuel. It should be noted that when one decides to use filler materials, containment becomes necessary, and the above advantages automatically apply to those utilizing filler materials. In addition, other advantages are possible. For example, by selecting the proper filler material one may (1) reduce corrosion of the fuel cladding, (2) increase the thermal conductivity of the contained fuel assembly, and (3) reduce criticality considerations by lowering the K effective (criticality constant) value of the encapsulated fuel assembly container.

On the negative side there are also disadvantages. The main disadvantage, of course, is economic. The second disadvantage is feasibility.

The raw materials, fabrication, and additional operations associated with the storage containers and the filler materials will add to the

cost of storage. This paper does not present an economic analysis but it does itemize the cost of the filler materials reviewed in the Appendix. These costs are presented as appropriate unit volume or unit weight costs and also as costs per container.

The feasibility of using containers and filler materials applies mainly to existing facilities, e.g., commercial power reactor sites. Many of these sites may not have the ability (without major modifications) to handle fuel containers and fill them with an encapsulating medium. In addition, their pool rack design may not accommodate fuel containers. New facilities dedicated to this operation, such as an AFR facility, would presumably be designed for canisterization prior to construction.

Another potential disadvantage of using filler materials involves the increased difficulty of retrieving the spent fuel if reprocessing is deemed appropriate at a later date. If the fuel has been stabilized in a solid matrix (for example, melting a metal, pouring it in a canister containing fuel, and allowing the package to solidify), the removal of the fuel could be quite difficult. In addition, the filler material could be slightly contaminated resulting in the generation of radioactive waste or additional process steps to decontaminate the filler material.

4.2 Fuel Container Closure Methods

The closure methods for the fuel container will be determined by the following criteria:

- Filler material
- Fuel container configuration (square or round)
- Fuel container material of construction
- Welding and cleanliness
- Leak-tightness integrity
- Fuel container top cap (method of installation)

The study basis is one unassembled PWR fuel assembly, or the fuel rods from two disassembled PWR fuel assemblies contained in a fuel container. All positioning, installation, and handling will be performed remotely in a hot cell environment.

Filler Materials

Depending on the type of filler material to be used to encapsulate the contained fuel, closure of the fuel container could be relatively simple or complex. Assuming air as filler material would only require that the top cap be "clipped" or locked into place; the resulting open seams would present no problems in the dry storage mode. Liquid or gas (other than air) as the filler material would require closure welding and nondestructive inspection of the weld to assure containment of the selected liquid/gas. Solid filler material could result in closure problems relating to effects from cleanliness to closure weld heat transfer characteristics.

Fuel Container Configuration

Fuel container configuration (whether a round or square can cross-section) would have little effect on installation of the top cap provided no welding was required to seal the seams between cap/container. If welding was required then the round container would be more adaptable to remote operation of commercially available orbital weld tracking equipment. The square can would necessitate modifications to assure weld bead and weld penetration consistency. Designing, fabricating and remotely operating/maintaining any welding equipment and positioning/support fixturing within a hot cell environment places a high cost on reliable support equipment.

Fuel Container Material of Construction

Considering the filler material to be installed and based on projected storage criteria, the use of thin walled (0.125" to 0.250") austenitic stainless steel would be the most likely candidate in fuel container construction. Carbon steel could also be employed for a slight reduction in cost and increased strength, but the cost advantage would probably be negated in the probable surface finishing operations and the increased strength would not be too important a consideration. Other materials of construction can be considered as candidates for construction but there is no advantage, based on present containment/storage criteria, to consider them either from the corrosion, economical or fabrication aspects. The top cap would be of the same material as the remainder of the container.

Welding and Cleanliness

Other than a container containing air as the filler material and possibly some solid materials, the closure seams between the top cap and container will require a hermetically sealed joint. The most likely closure process to be used would be welding. Based on the estimated material and material thickness noted previously, two methods of conventional welding can be considered, one of which would be limited by the material thickness -- laser welding. The other considered more readily adaptable to this type of closure welding would be pulsed gas tungsten arc (GTAW) welding having automated and wire feed capabilities. Both methods are industry-recognized and have been developed with associated equipment through hot cell process studies and techniques to give repeatable results and relatively-free maintenance operations. Both are adaptable for remote operation, although some special considerations may have to be given depending on the radiation levels at the container surface.

Both the laser and pulsed gas tungsten arc welding can be performed with the container in either the horizontal or vertical position, although the container in the horizontal position would be the most advantageous in minimizing the fixturing needed to position, track, and weld the closure.

Both weld processes have the advantage of making high quality welds in almost all metals and alloys, very little cleaning is required, little or no splatter and no slag is produced, and the weld pool is visible during welding. Heat input can be accurately controlled and the weld arc or impingement point can be accurately positioned and directed throughout the welding cycle. Laser welding, although a good choice for remote welding in a hot cell due to a lesser amount of equipment having to be located in the cell, has two disadvantages; material thickness limitations and the problems associated with positioning weld filler material in the weld joint remotely. The pulse gas tungsten arc welding equipment does not have these limitations. Both welding processes are capable of rewelding any areas found rejectable.

Leak-Tightness Integrity

The integrity of the top can/container will depend on the filler material installed and on the criteria established for the storage area. Containers "filled" with air most likely would not have the same integrity requirements as that for a gas such as helium, and may not even require a closure weld unless necessitated by structural (handling) requirements.

Where leak-tightness integrity is required, the previously discussed welding methods should be capable of making the quality weld necessary to meet leak-tightness requirements. Many industry-recognized non-destructive testing methods are available and with some modifications, adaptable to hot cell remote operation. These include, but are not limited to, helium leak testing, ultrasonic testing, and pressure testing.

Fuel Container Top Cap (Method of Installation)

The type of joint acceptable to contain the filler material, fuel assembly/rod debris, or "crud" will determine the method of installation of the top cap and whether a welded joint is required. Methods of installation include: (1) "clipping" the open seamed cap into the container, (strong enough to carry the weight or the loaded container through handling operations), (2) "clipping" but also welding the seams to contain the filler material and fuel, and (3) screwed top cans, nonwelded or welded (for round containers) with the top cap inserted and welded in position.

4.3 Summary of Appendix

A thermal analysis was performed, as shown in the Appendix of this report, involving the canisterized of intact and disassembled PWR spent fuel assemblies using various solid, liquid, and gaseous filler materials in the void spaces between the fuel pins. The maximum fuel pin cladding temperatures were calculated for five-year-cooled fuel assuming one kilowatt of decay heat per fuel assembly. The Appendix also includes an assessment of the alternative filler materials in terms of

physical properties, safety, ease of use (filling and removal), and cost.

It is interesting to note that when any one of the filler materials investigated (solid, liquid, or gas) were used, the maximum temperature of the disassembled fuel was less than that of the intact fuel, even though the disassembled fuel decay heat in the same storage volume is double that of intact fuel. This phenomenon occurs because disassembled fuel pins are in direct contact with one another and have a high conductivity compared with the filler materials.

For the dry storage of spent fuel it appears (see Tables 6 and 7 of Appendix) that air is the best filler media. As a filler material air costs nothing, is not corrosive to the cladding, is resistant to radiation damage, has insignificant weight, and is resistant to loss by leakage. The only negative factor for air, or any of the gases studied, is that the maximum fuel pin cladding temperature is higher than for solid or liquid fillers. However, the calculated 163°C (again see Table 6, Appendix) is still well below what would be regarded as detrimental to the fuel (about 380°C or 716°F) during extended storage.

The use of filler materials other than air for dry storage of spent fuel could only be justified if a specific criteria was deemed very important. For instance, containment: if one wanted to make absolutely sure that no fuel "leaked" out of potentially defective cladding one could pour a molten solid in the canister of fuel and allow it to solidify, thus encasing the fuel rods; or temperature: if a lower centerline temperature were required a liquid or solid filler might be chosen.

5.0 REFERENCES

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2. Anderson, K. J., Spent Fuel Dry Storage Studies at the Barnwell Nuclear Fuel Plant, Allied-General Nuclear Services, AGNS-35900-1.3-96 (September 1980).

AGNS-47921-1.3-143
APPENDIX

THERMAL ANALYSIS OF CANISTERIZED SPENT FUEL
USING VARIOUS FILLER MATERIALS

prepared for
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ABSTRACT

A thermal analysis was performed on intact and disassembled PWR spent fuel assemblies canisterized using various solid, liquid and gaseous filler materials in the void space between fuel pins. The maximum fuel pin cladding temperatures were calculated for five-year-cooled fuel with one kilowatt of decay heat per fuel assembly. This study includes a comparison of selection criteria for alternative filler materials in terms of physical properties, safety, ease of use (filling and removal) and cost.

INTRODUCTION

As requested by Allied-General Nuclear Services (AGNS) (1)*, Ridihaigh, Eggers and Associates, Inc. (REA) performed thermal analyses of alternative filler materials which could be used to encapsulate spent nuclear fuel in a canister. The purpose of these analyses is to determine which materials can maintain integrity at a given maximum fuel pin temperature while preventing the exterior of the canister from exceeding a given maximum storage pool temperature. A suitable filler material will conduct heat effectively within this range of maximum allowable temperatures. These thermal analyses calculate maximum fuel pin cladding temperatures to arrive at heat transfer effectiveness for each filler material.

Though heat transfer effectiveness is a primary consideration, other factors must also be taken into account when choosing a filler material. Other physical properties (density, melting point), corrosion resistance, ease of use and cost of a filler material must all be considered; special attention is paid to these factors in the final section of this report.

Preliminary Conditions

Preliminary investigation revealed that several classes of materials must be rejected due to questionable thermal stability or due to other properties which render them unsafe. For example, since the standard maximum allowable temperature for spent fuel stored for extended periods (5) is generally regarded to be about 380 C (716 F), it was also assumed that a filler material could be exposed to this temperature. For this reason, plastics in general were not considered as candidate materials, since most either melt or partially volatilize at temperatures less than 380 C.

Safety was another factor used to determine which filler material alternatives would undergo thermal analysis. Several heat transfer fluids were found to be unsafe based on their toxic and/or corrosive properties. Some liquid metals, such as sodium, present a fire hazard and were, therefore, not considered.

* See References at end of report.

Specification for Fuel and Canister

Five-year-cooled 17 X 17 pin PWR spent fuel in both intact and disassembled (i.e., two assemblies per canister) forms were used in these thermal analyses. For intact fuel, the canister was assumed to be 9.00 inches square inside and 9.25 inches square outside. For the case of two disassembled fuel assemblies, the same size canister was assumed with a 0.125-inch-thick diagonal divider plate. For both intact and disassembled fuel situations, the canister is assumed to be surrounded by water at 82 C (180 F) to allow for the possibility of storage in a wet or dry environment.

Table 1 presents the fuel specifications which were used in these analyses based on a 17 X 17 pin fuel assembly. The number of fuel pins in a 17 X 17 pin assembly is 264, which does not include the 24 control rods and one instrument tube that are assumed to be removed before storing the fuel in a canister.

The thermal analysis was performed with mathematical models of the PWR fuel assemblies with the aid of the TRUMP (3) heat transfer computer program. Results of standard heat transfer correlations (4) were utilized as input into the TRUMP computer program.

TABLE 1. PWR FUEL SPECIFICATIONS* USED IN THERMAL ANALYSES

Fuel (5-year-cooled)	17 x 17 PWR
Maximum enrichment (% U235)	4.1
Maximum burnup (MWD/MTU)	33,000
Maximum specific power (MW/MTU)	35
Assembly cross section (inches)	8.426 x 8.426
Active fuel pin length (feet)	12.0
Fuel pin overall diameter (inch)	0.374
Number of fuel pins in one assembly	264
Fuel loading (MTU)	0.480
Canister outside cross section (inches)	9.25
Canister wall thickness (inches)	0.125
Decay heat per PWR assembly (kW)	1.0
Number of assemblies per canister	
Intact assembly	1
Disassembled assemblies	2

* Based on Reference 2.

MAXIMUM FUEL PIN TEMPERATURES

The maximum fuel pin cladding temperatures were calculated for both the intact and disassembled PWR fuel assemblies. The results of these analyses are presented and discussed below for a number of alternative solid, liquid, and gaseous filler materials.

Intact PWR Fuel Assembly

Figure 1 illustrates one intact 17 X 17 pin fuel assembly in a 304 stainless steel canister. The canister was assumed to be vertically oriented, and the fuel assembly was assumed to be centered in the canister. The exterior surface of the canister was assumed to be 82 C (180 F), which is the maximum storage pool temperature sometimes specified for normal operation. The assumed fuel rod diameter was 0.374 inch, and the center-to-center pin spacing was 0.496 inch. The solid, liquid, or gas media surrounds the fuel pins and fills the empty control rod and instrument guide tubes. Due to the assumed symmetry, the four central fuel pins operate at the maximum temperature as illustrated in Figure 1.

Solid Filler Materials

The calculated maximum fuel pin temperature is presented in Figure 2 for a wide range of thermal conductivity associated with alternative solid filler materials. To illustrate the use of these data, several candidate filler materials are indicated at their respective values of thermal conductivity. Many of the solid filler materials indicated in Figure 2 are granular with air or, in the case of UO_2 , helium filling the interstices of the solid filler materials.

The various physical properties and characteristics used in the assessment of the alternative filler materials are summarized in Table 2. All are inorganic and all but two, zinc and lead, have melting temperatures greater than 380 C maximum limit for long-term fuel storage. Zinc and lead are the only materials that would be placed in a canister in the molten state and

17x17 PINS FUEL ASSEMBLY OVERALL CROSS-SECTION= 8.426 x 8.426

C-0781-120

- ⊗ INSTRUMENT TUBE LOCATION
- ⊕ 264 FUEL PINS
- ⊗ HOTTEST FUEL PINS

DIMENSIONS ARE IN INCHES

FIGURE 1. LOCATION OF HOTTEST FUEL PINS IN PWR ASSEMBLY

FIGURE 2. MAXIMUM FUEL PIN CLADDING TEMPERATURE FOR GRANULAR SOLIDS AMONG FUEL PINS WITH ONE INTACT PWR FUEL ASSEMBLY IN A CANISTER

TABLE 2. SELECTED THERMOPHYSICAL PROPERTIES OF
SOLID AND GRANULAR SOLID FILLER MATERIALS

Solid-Gas Mixture		Solid Density, g/cm ³	Thermal Conductivity x 10 ⁵ , cal/s-cm-C			Solid Melting Temperature, C	Reference Number
Solid	Gas		Solid	Gas ¹	Solid-Gas Mixture		
Copper (147 μ -589 μ) ²	air	8.97	94000	6.5	163	1083	6, 7, 8
Aluminum	air	2.70	45000	6.5	- ³	660	6, 7
Graphite	air	1.50	36000	6.5	283	3700	6, 7, 9
Zinc (5 μ)	air	7.14	27000	6.5	110	283	6, 7, 8
Carbon steel (71 μ)	air	7.85	11000	6.5	60	1426	6, 7, 8
Lead	air	11.3	8300	6.5	- ³	327	6, 7
B ₄ C	air	2.52	5000	6.5	- ³	2450	7, 10
UO ₂ powder	helium	10.8	1430	36.6	350	2750	7, 11, 12
Alumina	air	4.00	790	6.5	161	2050	9
Sand (22 μ)	air	1.52 ⁴	620	6.5	61	-	6-9
Glass (80 μ)	air	2.22	240	6.5	44	1200	6, 7, 8
Mortar	-	2.20	220	-	-	-	9
Rock, glass wool	air	0.16 ⁴	-	6.5	12	-	6, 7

¹ Based on a nominal temperature of 38°C.² Number in parentheses refers to average or range of particle sizes in units of microns.³ Value not known, but believed to be in the range between the previous table entry and the following one.⁴ Bulk material density.

solidified. The others are placed in a canister in particle form with air or some other gas filling the void spaces among particles, except mortar which is a continuous mass. The high thermal conductivity values corresponding to zinc and lead are off the scale in Figure 2, and the temperature differential from the center of the canister to its surface is negligible. Lead or zinc could be utilized as spherical particles, but as Table 2 indicates, the thermal conductivity of zinc decreases from 0.27 cal/s-cm-C in solid form to 0.0011 cal/s-cm-C in particle form.

The thermal conductivities of several of the materials in granular form are not known, but their approximate values can be deduced from the data in Figure 2 and Table 2. For example, the thermal conductivity of solid zinc is between those of steel and copper, and in Figure 2, the value for zinc particles in air also is between those of steel and copper spheres in air. Therefore, one may assume that the value for aluminum spheres in air is between those of zinc and copper, and the value for lead spheres in air is between those of glass beads and steel spheres in air. For the lowest thermal conductivity (wool) in Figure 2, the maximum temperature differential from the hottest fuel pin to the canister surface is approximately 130 C.

Liquid Filler Materials

The calculated maximum fuel pin temperatures are summarized in Figure 3 for the case of liquid filler material surrounding the fuel pins of an intact PWR fuel assembly. Four common heat transfer liquids are indicated at their respective values of thermal conductivity. For the lowest value of thermal conductivity studied (silicone), the maximum temperature differential from the hottest fuel pin to the canister temperature is 17 C.

Table 3 presents various physical properties useful in evaluating the feasibility of each liquid filler material considered. Water has the greatest value of thermal conductivity.

FIGURE 3. MAXIMUM FUEL PIN CLADDING TEMPERATURE FOR LIQUIDS AMONG FUEL PINS WITH ONE INTACT PWR FUEL ASSEMBLY IN A CANISTER

TABLE 3. SELECTED THERMOPHYSICAL PROPERTIES
OF LIQUID FILLER MATERIALS FOR
RANGES OF TEMPERATURES AND PRESSURES

Liquid Filler Material	Density, g/cm ³	Boiling Temperature, C	Pressure At Boiling, psia	Thermal Conductivity x 10 ⁵ , cal/c-cm-C	Ref. No.
Water	0.956	100	14.7	160	13
	0.786	260	680.8	145	
Ethylene Glycol/ Water	1.013	100	13.8	96	14
	0.963	177	103.0	87	
Dowtherm	0.860	258	14.7	24	6,15
	0.739	380	119.0	20	
Silicone	0.900	100	0.077	28	15,16
	0.744	300	20.9	17	

Gaseous Filler Materials

The maximum calculated fuel pin temperature associated with gaseous filler materials is summarized in Figure 4. Note that of the five gases considered, the thermal conductivity values for argon and carbon dioxide are approximately equal, as are nitrogen and air. The maximum temperature differential from the hottest fuel pin to canister temperature is 93 C. Steam was initially considered, but was eventually rejected because its low thermal conductivity and possible overpressurization of a canister at high temperature are undesirable characteristics. A comparison of the thermal conductivities of the alternative gaseous filler materials is summarized in Table 4.

Also, a maximum fuel pin cladding temperature of 210 C was estimated for the hottest pin with no coolant; i.e., a vacuum in which all heat transfer was by thermal radiation to the canister surface. The temperature difference between 210 C and the curve in Figure 4 is the contribution of thermal conductivity of the alternative gaseous filler materials.

Disassembled PWR Fuel Assemblies

The disassembled PWR fuel assemblies are illustrated in Figure 5. For uniformity in handling and storage, the exterior cross-sectional dimensions of the canister are the same as those for the intact fuel assembly. The diagonal separator plate increases structural rigidity and separates the fuel for purposes of accountability. The canister surface temperature was assumed to be 82 C (180 F), the same assumption made for intact fuel. The locations of the hottest fuel pins are illustrated in Figure 5. The disassembled fuel was analyzed as if it were arranged in a square-pitch lattice.

Essentially, the disassembled fuel differs from the intact fuel in number of fuel pins, arrangement in canister and existence of a dividerplate. All three of these are salient features in determining heat transfer effectiveness.

FIGURE 4. MAXIMUM FUEL PIN CLADDING TEMPERATURE FOR GASES AMONG FUEL PINS WITH ONE INTACT PWR FUEL ASSEMBLY IN A CANISTER

TABLE 4. SELECTED THERMOPHYSICAL PROPERTIES
OF GASEOUS FILLER MATERIALS

Gas	Density ¹ , g/cm ³	Thermal Conductivity ² x 10 ⁵ , cal/c-cm-C	Ref. No.
Helium	0.000164	42.6	7,9
Air	0.00120	8.04	7,9
Nitrogen	0.00120	7.95	7,9
Steam	0.000257	6.22	13
CO ₂	0.00184	5.88	7,9
Argon	0.00166	5.32	7,9

¹ Based on temperature of 20°C and pressure of 14.7 psia.

² Based on temperature of 127°C and pressure of 14.7 psia.

SQUARE-LATTICE PACKING ASSUMED IN ANALYSIS

HOTTEST FUEL PINS

528 (0.374 D) PWR FUEL PINS (2 ASSEMBLIES)

DIMENSIONS ARE IN INCHES

FIGURE 5. TWO DISASSEMBLED PWR FUEL ASSEMBLIES IN A CANISTER

Solid Filler Materials

The maximum calculated fuel pin cladding temperature is summarized in Figure 6 for the case of solid filler materials surrounding the consolidated fuel pins. The maximum fuel pin cladding temperatures corresponding to a given thermal conductivity value is less than that for an intact fuel assembly. This difference occurs because the aggregate heat transfer path through the solid filler material from the center of the assembly to the canister surface is less in the case of the disassembled fuel than in the case of the intact fuel assembly. A comparison of Figures 1 and 5 show that the amount of void space occupied by filler material is greater in the case of the intact assembly than it is in the disassembled case. Also, a small quantity of heat is conducted from the center of the canister by the steel divider plate, which lowers the maximum fuel pin cladding temperature.

Liquid Filler Materials

The calculated maximum fuel pin cladding temperature is summarized in Figure 7 for the liquid filler materials considered. The maximum temperature differential is 10°C at the lowest value of thermal conductivity considered.

Gaseous Filler Materials

The maximum calculated fuel pin cladding temperature is summarized in Figure 8 for gaseous filler materials in a consolidated fuel canister. Maximum cladding temperatures are a few degrees less than the corresponding maximum cladding temperatures for the case of an intact fuel assembly.

The maximum fuel pin cladding temperature for the case of a vacuum (i.e., no coolant) was calculated to be 210 C. Radiation form factors are greater for more closely spaced fuel pins, conduction through and around fuel pins, and the conduction of the diagonal plate offsets the effect of radiating across a greater number of rows of fuel pins.

FIGURE 6. MAXIMUM FUEL PIN CLADDING TEMPERATURE FOR GRANULAR SOLIDS AMONG FUEL PINS WITH TWO DISASSEMBLED PWR FUEL ASSEMBLIES IN A CANISTER

FIGURE 7. MAXIMUM FUEL PIN CLADDING TEMPERATURE FOR LIQUIDS AMONG FUEL PINS WITH TWO DISASSEMBLED PWR FUEL ASSEMBLIES IN A CANISTER

FIGURE 8. MAXIMUM FUEL PIN CLADDING TEMPERATURE FOR GASES AMONG FUEL PINS WITH TWO DISASSEMBLED PWR FUEL ASSEMBLIES IN A CANISTER

COMPARATIVE ASSESSMENT OF ALTERNATIVE
FILLER MATERIALS

Comparison of Maximum Temperatures

From the data in Table 5, it is clear that when any of the filler materials investigated were used, the maximum temperature of the disassembled fuel was less than that of the intact fuel. This occurred despite the fact disassembled fuel has twice as many fuel pins and twice as much decay heat.

This effect was most evident when solid materials were used for two reasons. First, because conducting path lengths through solids are much shorter in the disassembled fuel case than they are for relatively widely-spaced intact fuel; thus, causing a decreasing temperature. Second, because solid fillers have low conductivity, the path of least thermal resistance in the disassembled fuel case is through the relatively high conductivity fuel pins, thereby, decreasing temperatures for disassembled fuel.

Table 5 shows that gaseous filler materials induce lower maximum temperatures than solids. This is because conduction through gases is secondary to heat transfer by thermal radiation. Again, when using gaseous filler materials, maximum temperatures are lower for disassembled fuel than for intact fuel.

The conductivity of liquids is relatively high; thus, liquid filler materials induce the lowest maximum temperatures of the three materials studied. Note that of the three filler material types studied, liquids produced the smallest difference in maximum temperatures between the disassembled and intact fuel cases.

Comparison of Selection Criteria

A comparison of selected characteristics of the alternative filler materials analyzed here is presented in Tables 6 and 7 for the intact and disassembled fuel assemblies, respectively.

TABLE 5. MAXIMUM FUEL PIN CLADDING TEMPERATURES WITH
ALTERNATIVE FILLER MATERIALS FOR PWR INTACT
AND DISASSEMBLED FUEL ASSEMBLIES

Filler Material Type	PWR Intact	PWR Disassembled
Solid	212 C	166 C
Liquid	99 C	92 C
Gaseous	175 C	156 C

TABLE 6. COMPARISON OF SELECTED CHARACTERISTICS OF ALTERNATIVE FILLER MATERIALS USED WITH INTACT FUEL ASSEMBLIES

Filler Material	Maximum Calculated Fuel Pin Cladding Temperature, C	Weight, kg		Estimated ¹ Filler Material Cost per Canister, dollars	Resistance to Corrosion or Oxidation	Criticality Safety ² Benefits (Relative to Air)	Resistance to Radiation Damage	Resistance to Loss by Leakage
		Filler Material	Fuel Assembly and Filler and Canister					
<u>Solids</u>								
Copper spheres	85	560	1350	6,720	Excellent	Fair	Excellent	Excellent
Aluminum spheres	87	170	960	620	Excellent	Fair	Excellent	Excellent
Graphite powder	86	70	860	100	Excellent	Poor	Excellent	Excellent
Zinc spheres	98	1000	1790	11,000	Excellent	Fair	Excellent	Poor (if liquid)
Carbon steel spheres	104	490	1280	360	Excellent	Fair	Excellent	Excellent
Lead	84	1580	2370	3,820	Excellent	Fair	Excellent	Poor (if liquid)
B ₄ C powder	98	160	950	6,700	Excellent	Good	Excellent	Excellent
UO ₂ powder	84	480	1270	37,000	Excellent	Fair	Excellent	Excellent
Alumina powder	104	250	1040	2,500	Excellent	Fair	Excellent	Excellent
Sand	104	210	1000	200	Excellent	Fair	Excellent	Excellent
Glass spheres	109	140	930	280	Excellent	Fair	Excellent	Excellent
Mortar	86	310	1100	470	Excellent	Fair	Excellent	Excellent
<u>Liquids</u>								
Water	86	130	920	30	Fair	Poor	Fair	Poor
Ethylene Glycol/Water	88	140	930	< 67	Fair	Poor	Poor	Poor
Dowtherm A	95	120	910	430	Fair	Poor	Poor	Poor
Silicone	99	130	920	800	Fair	Poor	Poor	Poor
<u>Gases</u>								
Argon, CO ₂	175	~ 0	790	< 20	Excellent	Excellent	Excellent	Poor
Nitrogen	163	~ 0	790	< 20	Excellent	Excellent	Excellent	Poor
Air	163	~ 0	790	0	Excellent	Excellent	Excellent	Excellent
Helium	112	~ 0	790	< 50	Excellent	Excellent	Excellent	Poor

APPENDI
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1. Cost figures are based on catalog, oral quotation or engineering estimate and should be considered only as approximations
2. Of these materials, gases are the most criticality safe, since they do not alter the direction or speed of neutrons. Hydrogenous liquids and graphite are good moderators, which tend to increase criticality, and are rated poor. The other materials may absorb, reflect, or moderate neutrons and this interaction is difficult to define without a detailed criticality analysis, thus they were rated fair. When any of these materials are used, a detailed criticality analysis should be performed.

TABLE 7. COMPARISON OF SELECTED CHARACTERISTICS OF ALTERNATIVE FILLER MATERIALS USED WITH DISASSEMBLED FUEL ASSEMBLIES

Filler Material	Maximum Calculated Fuel Pin Cladding Temperature, C	Weight, kg		Estimated ¹ Filler Material Cost per Canister, dollars	Resistance to Corrosion or Oxidation	Criticality Safety ² Benefits (Relative to Air)	Resistance to Radiation Damage	Resistance to Loss by Leakage
		Filler Material	Fuel Assembly and Filler and Canister					
<u>Solids</u>								
Copper spheres	84	220	1510	2640	Excellent	Fair	Excellent	Excellent
Aluminum spheres	86	70	1360	250	Excellent	Fair	Excellent	Excellent
Graphite powder	85	30	1320	45	Excellent	Poor	Excellent	Excellent
Zinc spheres	97	180	1470	1980	Excellent	Fair	Excellent	Poor (if liquid
Carbon steel spheres	102	190	1480	140	Excellent	Fair	Excellent	Excellent
Lead	83	280	1570	680	Excellent	Fair	Excellent	Poor (if liquid
B ₂ C powder	97	60	1350	2500	Excellent	Good	Excellent	Excellent
UO ₂ powder	83	190	1480	14600	Excellent	Fair	Excellent	Excellent
Alumina powder	102	100	1390	1000	Excellent	Fair	Excellent	Excellent
Sand	102	80	1370	100	Excellent	Fair	Excellent	Excellent
Glass spheres	108	50	1340	140	Excellent	Fair	Excellent	Excellent
Mortar	85	120	1410	180	Excellent	Fair	Excellent	Excellent
<u>Liquids</u>								
Water	84	52	1342	< 15	Fair	Poor	Fair	Poor
Ethylene Glycol/Water	86	55	1345	< 34	Fair	Poor	Poor	Poor
Dowtherm A	90	47	1337	170	Fair	Poor	Poor	Poor
Silicone	92	49	1339	300		Poor	Poor	Poor
<u>Gases</u>								
Argon, CO ₂	156	~ 0	1290	< 10	Excellent	Excellent	Excellent	Poor
Nitrogen	143	~ 0	1290	< 10	Excellent	Excellent	Excellent	Poor
Air	143	~ 0	1290	0	Excellent	Excellent	Excellent	Excellent
Helium	102	~ 0	1290	< 25	Excellent	Excellent	Excellent	Poor

APPENDIX
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1. Cost figures are based on catalog, oral quotation or engineering estimate and should be considered only as approximations
2. Of these materials, gases are the most criticality safe, since they do not alter the direction or speed of neutrons. Hydrogenous liquids and graphite are good, moderators, which tend to increase criticality and are rated poor. The other materials may absorb, reflect, or moderate neutrons and this interaction is difficult to define without a detailed criticality analysis, thus they were rated fair. When any of these materials are used, a detailed criticality analysis should be performed.

Preference for a filler material depends on the selection criteria used. For example, if cost were to be minimized, then air would be the preferred filler material. If cost and peak cladding temperature were to be minimized, then mortar or sand might be selected. If reliability were to be maximized, then air would be selected as the filler material (assuming the canisters are stored in an environment surrounded by air). If corrosion resistance were a criterion, the gases or solids could be used reliably. Liquids are potentially corrosive unless their pH's are increased into a nonaggressive range and they are modified by an inorganic corrosion inhibitor and sufficient quantities of an oxygen scavenger.

The comparison data provided in Tables 6 and 7 should be considered as an approximation or generalization. More specific comparison data requires a more detailed description of the spent fuel storage environment such as ambient temperature, atmosphere, and retrievability requirements.

Additional Considerations

This study considers some materials which are currently available for use as fillers in spent fuel assembly interim storage situations. A number of variables in choosing a filler material have been addressed in this report. In addition to heat transfer effectiveness, criticality safety, resistance to corrosion, and radiation damage or loss by leakage, the selection of a filler material also depends upon the design criteria of the canister in which it is stored. The design of a canister could render some filler materials impractical, regardless of the attractiveness of their performance in a thermal analysis or other selected characteristics. For example, if the canister is designed to permit retrievability of spent fuel, materials such as mortar, lead or zinc might be rejected due to the difficulty of separating them from the fuel pins.

In addition, the potential of long-term storage for a particular canister must be borne in mind when selecting a filler material. It is known that, during long-term storage periods, nuclear radiation effects are deleterious to hydrocarbons such as plastics. On this basis, rather than on a thermal analysis basis, ethylene glycol, DowthermTM and silicone might be rejected as well.

Cases for Further Study

Filler materials which were not considered as possible alternatives in this study but which, under certain conditions, might be viable alternatives are: TeflonTM, boron carbide, borated steel spheres and cadmium copper spheres and mineral wool.

For example, if a canister were to be used for interim storage only and if its surface temperature could be maintained at 82 C as assumed in the thermal analysis, TeflonTM, which can withstand 285 C (545 F) continuously might be used as a filler material. On the other hand, if storage conditions were such that criticality safety must be optimized, boron carbide might be preferred to other filler materials. Similarly, borated steel spheres and cadmium copper spheres may also improve criticality safety margins or canister packing densities. If conditions require minimization of overall weight, one of the thermal insulations such as mineral wool might be acceptable.

The process of filling the voids around the pins and the settling after filling are considered to be potential problems with solid fillers, particularly in the case of low density materials.

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