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REGULATORY FIRE TEST REQUIREMENTS FOR PLUTONIUM AIR TRANSPORT PACKAGES: JP-4 OR JP-5 VS. JP-8 AVIATION FUEL

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ABSTRACT

For certification, packages used for the transportation of plutonium by air must survive the hypothetical thermal environment specified in 10CFR71.74(a)(5). This regulation specifies that "the package must be exposed to luminous flames from a pool fire of JP-4 or JP-5 aviation fuel for a period of at least 60 minutes." This regulation was developed when jet propellant JP-4 and JP-5 were the standard jet fuels. However, JP-4 and JP-5 currently are of limited availability in the United States of America. JP-4 is very hard to obtain as it is not used much anymore. JP-5 may be easier to get than JP-4, but only through a military supplier. The purpose of this paper is to illustrate that readily-available JP-8 fuel is a possible substitute for the aforementioned certification test. Comparisons between the properties of the three fuels are given. Results from computer simulations that compared large JP-4 to JP-8 pool fires using Sandia's VULCAN fire model are shown and discussed. The paper recommends JP-8 as an alternate fuel that complies with the thermal environment implied in 10CFR71.74.

INTRODUCTION

The certification of packages for air transportation of plutonium is governed in the United States of America by the NRC 10CFR71.74 [1]. This regulation states that the package must be exposed to luminous flames of JP-4 or JP-5 aviation jet fuel for a period of at least 60 minutes. JP-4 and JP-5 were first developed in the 1950s as jet engine fuels and were primarily used by the military establishment in Great Britain and in the USA. Both jet fuels were first specified in NUREG-0360 [2].

The lack of readily available JP-4 and JP-5 presents a problem for research and testing institutions such as Sandia National Laboratories. Obtaining JP-4 and JP-5 for testing purposes is difficult and expensive since their supply and distribution sources are limited. JP-8, on the other hand, is widely available due to its high demand these days in US military aircraft.

In this paper, the chemical properties and thermal behavior of JP-4, JP-5, and JP-8 fires are examined. The chemical properties of JP-4, JP-5, and JP-8 are compared to determine the suitability of JP-8 as an alternative aviation fuel for use in air-transport package certification tests. Results of fire simulations using JP-4 and JP-8 formulations are then compared to determine the difference in the thermal behavior of the resulting fire plumes. Some suggestions to work with challenges associated with the thermal test specified in 10CFR71.74(a)(5) are then discussed in light of these simulation results.

JP-4, JP-5, AND JP-8 FUEL PROPERTIES

When NUREG-0360 was first written, JP-4 was widely available. Because of the low flash point (-18°C) and static electricity build up, the US military phased out JP-4 and replaced it with the less volatile JP-8 jet fuel in 1996. Due to its cold weather performance (freezing point of -58°C), JP-4 still finds a demand in the northern parts of the continental USA and in Alaska, but its supply is limited to and concentrated in those areas where it is used.

JP-5 was specifically developed for use in aircrafts stationed aboard aircraft carriers where the risk of fires is great. JP-5 has a higher flash point (60°C) than JP-8, but it's also more expensive, limiting its use to aircraft carriers. JP-5 remains the primary jet fuel for the US Navy. Thus, the supply of JP-5 has been mostly driven by the military demand as it is not cost effective for commercial use.

JP-8, a military-grade version of the commercially available Jet-A, was first used by NATO in the late 1970s. JP-8 has a higher flash point (38°C) than JP-4 but lower than JP-5. JP-8 is also used in other military equipment. JP-8 and Jet-A are the most widely used jet fuels in the world.

Table 1 shows additional properties of JP-4, JP-5, and JP-8. Data on the first five properties in Table 1 are from Reference 3. The heat of vaporization for JP-4 is taken from Reference 4. The heat of vaporization for JP-8 is assumed to be identical to JP-5, and is taken from Reference 5. As seen in Table 1, there are only slight differences in the first three properties listed: approximate chemical formulation, density, and heat of combustion. JP-4 has a higher hydrogen/carbon ratio (2.22) than JP-8 (1.92). JP-8 is 6% more dense than JP-4. However, the heat of combustion is virtually the same for both fuels on a mass basis. Other properties such as specific heat and thermal conductivity show very little difference also.

Table 1. Properties of JP-4, JP-5, and JP-8 Aviation Fuels

Property	JP-4	JP-5	JP-8
Approximate Chemical Formulation	C_9H_{20}	-	$C_{12}H_{23}$
Density, kg/m^3	760 @ 20°C	814 @ 20°C	808 @ 20°C
Heat of Combustion (MJ/kg)	43.6	42.6	43.2
Boiling Range, °C	66-246	170-269	177-266
Vapor Pressure @ 50°C, kPa	27	< 1.5	1.5
Heat of Vaporization (kJ/kg) @ average T_{boil}	252	280	280
Fuel Consumption Rate (mm/min)	4.4	-	4.7

A significant difference is seen in the boiling temperature range. JP-4 begins to distill at 66°C, and is completely in the vapor phase at 246°C. JP-8 does not begin to distill until 177°C, and must reach a temperature of 266°C before it will be completely in the vapor phase. The ability to heat fuel to reach its boiling point has a direct influence on the ease with which a fuel is ignited and a fire is sustained. A comparison of the vapor pressure at 50°C indicates that JP-4 has a vapor pressure that is 18 times greater than that of JP-8. This illustrates the essential difference between a high volatility and a low volatility fuel: more fuel in the vapor phase at a given temperature makes the higher volatility fuel easier to ignite. It is for this reason (ease of ignition) that JP-8 is generally regarded as being a safer fuel than JP-4.

It is important to note that JP-4, while substantially more volatile than JP-8, requires only slightly less energy per kg (10% less) to vaporize once distillation is initiated. Thus, it is not merely the heat of vaporization that determines the volatility of a given fuel, but the combination of sensible and latent heat required to vaporize the fuel. The sensible heating requirement (energy required to heat fuel to its average distillation temperature) for JP-8 (461 kJ/kg) is about 40% higher than for JP-4 (326 kJ/kg). Thus, the total energy required for JP-8 to be heated to its distillation temperature and vaporize (461 + 280 = 741 kJ/kg) is about 30% greater than for JP-4 (326 + 252 = 578 kJ/kg).

The comparison above also demonstrates that the sensible heating requirements for jet fuels are not negligible. In fact, for JP-8 the sensible heating requirements are 1.7 times greater than the latent heat requirements. This observation is important for pool fire modeling. The transient heating of a pool of jet fuel into its distillation regime is non-negligible relative to the energy required to vaporize the fuel. Therefore, if one is interested in correctly modeling/simulating the duration of a jet fuel pool fire, the transient heat up of the fuel must be taken into account.

NUMERICAL SIMULATIONS

Numerical simulations of large JP-4 and JP-8 pool fires have been performed using a fire field model to investigate the differences between fires resulting from the two fuels. The field model used for these calculations (VULCAN [6]) resulted from a joint development effort at Sandia National Laboratories and SINTEFINTH, and is based on the KAMELEON fire model developed at SINTEFINTH [7]. The numerical method employed is a finite volume solution of the basic equations of fluid dynamics, using mathematical submodels to represent the remaining physical phenomena. The most important of these submodels are: the k-epsilon turbulence model [8], the Eddy Dissipation Concept combustion model [9], and the soot model of Magnussen [10]. Thermal radiation is solved using a three-dimensional discrete transfer model [11]. The calculations are three-dimensional, transient, and elliptic.

Results of calculations for 19 m diameter pools of JP-4 and JP-8 are briefly summarized in this paper. Calculations were conducted for both zero and non-zero wind conditions, and only the fully-developed burning regimes were compared. Very little difference is observed in the projected flame shape, flame height, and flame temperature for the two fuels in Figure 1. This figure shows the maximum temperatures along the line-of-sight projected onto a vertical plane for a 1.3 m/s wind. Most of the flame volume is at temperatures between 1300-1500K for both fuels.

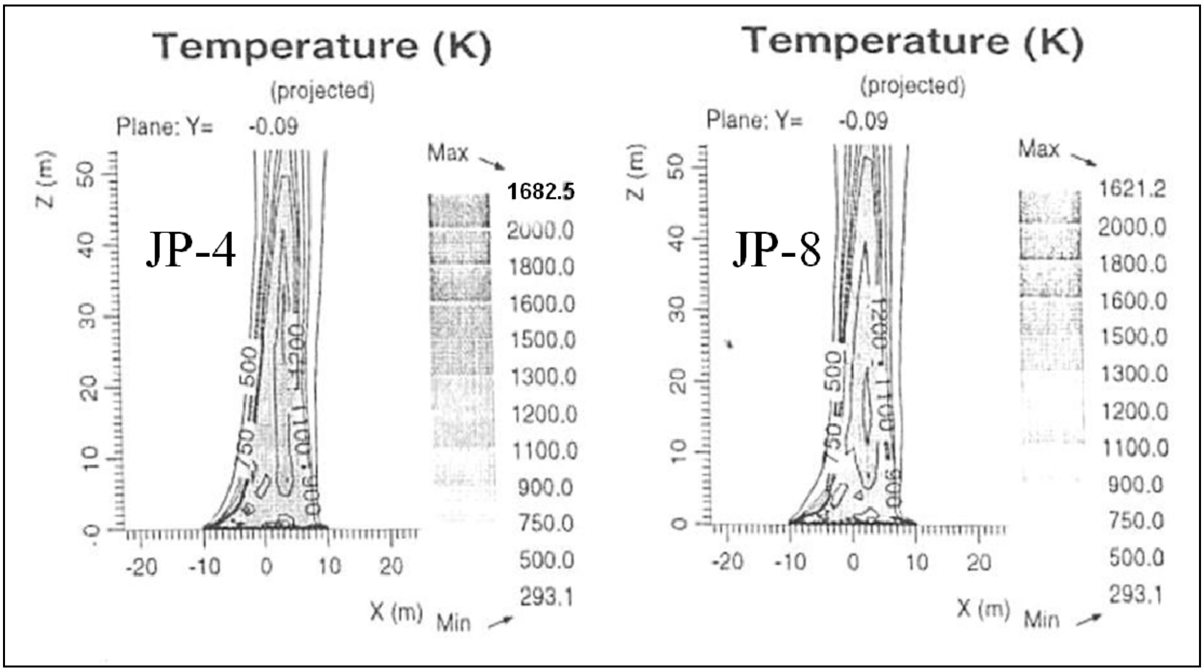

Figure 1. Comparison of Calculated JP-4 and JP-8 Flame Shape, Height, and Temperature (1.3 m/s wind from left; 19 m diameter pool fire)

A vertical plane through the centerline of the fire (not projected) is shown in Figure 2 for both fuels. The two fuels produce fires with counter-rotating vortices on the leeward side of the pool. These are the high temperature regions shown in Figure 2. Some differences are noticeable near the pool centerline, immediately above the pool surface. Figure 2 shows that the JP-4 fire has a low temperature region immediately above the pool surface (as indicated by the region below the 1300K contour) that extends somewhat higher above the pool. This trend is consistent with the existence of a more pronounced fuel vapor dome in this region for the JP-4 fuel relative to the JP-8 fuel. Fuel concentrations in the vapor dome are rich enough to limit the combustion process in this region.

Calculated heat fluxes to the pool surface are slightly lower for the JP-4 fuel than the JP-8 fuel. This is consistent with the lower temperatures in the JP-4 vapor dome region relative to JP-8. As shown in Figure 1, the influence of wind on the calculations did not result in significant differences between the two fuels. Large counter-rotating vortical structures were observed on the leeward edge of the pool for both fuels in all 1.3-2.5 m/s wind calculations. In general, the calculations indicate that there is not a significant difference between flame shapes, heights, and temperatures (although the fuel vapor dome is somewhat larger for JP-4) for fires resulting from the two fuels once they have reached fully-developed burning.

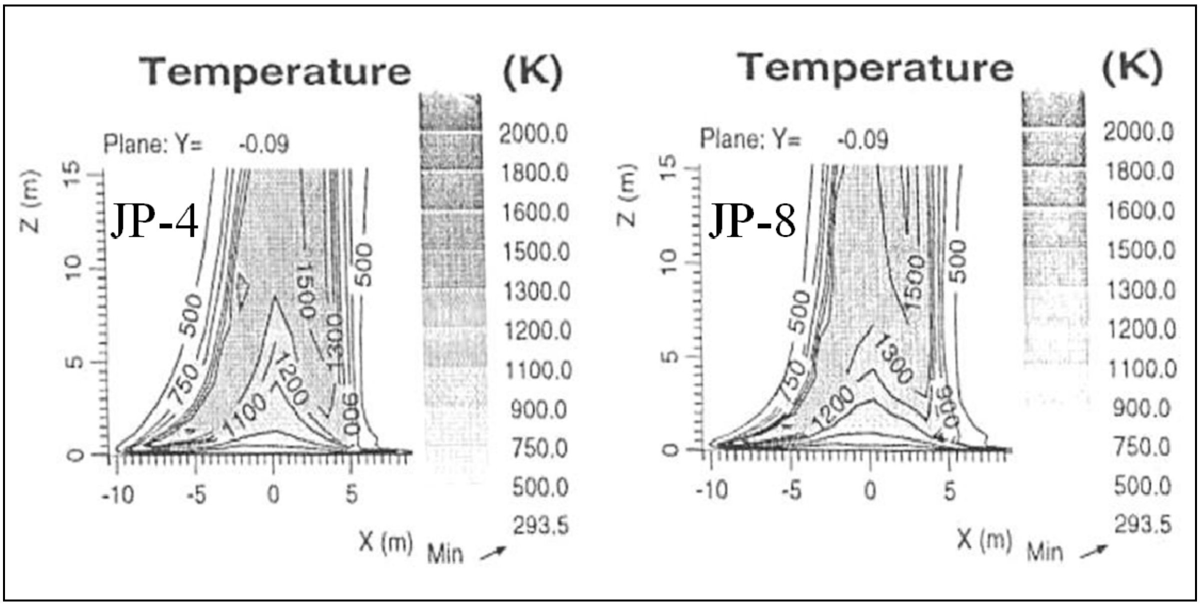

Figure 2. Comparison of Calculated Temperatures Showing Fuel Vapor Dome Region (1.3 m/s wind from left; 19 m diameter pool fire)

LARGE-SCALE TESTS

Large-scale tests (19 m diameter) with pools of JP-4 and JP-8 have been conducted at the Naval Air Warfare Center, China Lake, California. Tests with JP-8 indicate that longer times are required (compared to JP-4) to reach the point of fully-developed burning, where the flame shape no longer increases in size. For this reason, subsequent tests with JP-8 were often initiated by igniting gasoline that had been poured on top of the JP-8 to accelerate the flame spread over the surface and reduce the time necessary to reach fully-developed burning. This difference is directly attributable to the higher distillation temperatures of JP-8 relative to JP-4. JP-8 requires more energy to heat to the distillation range than JP-4, and thus requires a longer time to produce a fully-developed fire.

The test data corroborates the numerical simulations: once fully-developed burning conditions have been reached, there is little difference between the video recordings of flame shape and flame height, or between thermocouple measurements for the two fuels. Analysis of thermocouple measurements has been used to estimate the extent of the fuel vapor dome. As expected and as predicted by the numerical simulations, preliminary test results indicate that the fuel vapor dome is somewhat larger for the JP-4 fuel relative to JP-8.

It was also observed in the tests that JP-8 required 1.5-2 times as long to burn the same amount of fuel compared to JP-4. As discussed previously, this is due to the 30% larger total heating requirements for JP-8 compared to JP-4 as well as the substantially longer times required to reach fully-developed burning conditions for JP-8.

REGULATORY DISCUSSION

Regarding the certification of packages designed for the transport of plutonium by air, 10CFR71.74(a)(5) states:

"The package must be exposed to luminous flames from a pool fire of JP-4 or JP-5 aviation fuel for a period of at least 60 minutes. The luminous flames must extend an average of at least 0.9 m (3 ft) and no more than 3 m (10 ft) beyond the package in all horizontal directions. The position and orientation of the package in relation to the fuel must be that which is expected to result in maximum damage at the conclusion of the test sequence. An alternate method of thermal testing may be substituted for this fire test, provided that the alternate test is not of shorter duration and would not result in a lower heating rate to the package. At the conclusion of the thermal test, the package must be allowed to cool naturally or must be cooled by water sprinkling, whichever is expected to result in maximum damage at the conclusion of the test sequence."

This regulatory statement, as it stands, does not allow the use of alternative fuels in tests designed for certification of air transport containers in its strictest sense. However, as it has been shown, there is very little difference between JP-4 and JP-8 fires. While it is true that JP-8 fires require more time to become fully-developed, both tests and simulation results indicate that the resulting fire environments are very similar.

Additionally, 10CFR71.74(a)(5) does not define the test article location, the ambient conditions, and the characteristic temperatures of the fire as 10CFR71.73(c)(4) does. 10CFR71.73(c)(4) states:

"Exposure of the specimen fully engulfed, except for a simple support system, in a hydrocarbon fuel/air fire of sufficient extent, and in sufficiently quiescent ambient conditions, to provide an average emissivity coefficient of at least 0.9, with an average flame temperature of at least 800°C (1475°F) for a period of 30 minutes, or any other thermal test that provides the equivalent total heat input to the package and which provides a time averaged environmental temperature of 800°C. The fuel source must extend horizontally at least 1 m (40 in), but may not extend more than 3 m (10 ft), beyond any external surface of the specimen, and the specimen must be positioned 1 m (40 in) above the surface of the fuel source. For purposes of calculation, the surface absorptivity coefficient must be either that value which the package may be expected to possess if exposed to the fire specified or 0.8, whichever is greater; and the convective coefficient must be that value which may be demonstrated to exist if the package were exposed to the fire specified. Artificial cooling may not be applied after cessation of external heat input, and any combustion of materials of construction, must be allowed to proceed until it terminates naturally."

Comparing 10CFR71.74 with 10CFR71.73, one can notice the following differences:

- **Fuel:** JP-4/5 vs. hydrocarbon
- **Test Conditions:** Ambient conditions specified in 71.73 and not in 71.74
- **Fire emissivity:** 71.73 specify a fire emissivity of "at least 0.9" and 71.74 does not specify a fire emissivity
- **Position:** package height not specified in 71.74
- **Position:** 71.73 specify "extent of fuel source" (at least 1 but no more than 3 meters) and 71.74 specifies a minimum and maximum "average" extent of "luminous flames" beyond

the package in all horizontal directions. This requirement in 71.74 can be difficult to prove in practice.
- **Alternate Test:** no temperature specified in 71.74
- **Alternate Test:** 71.73 “equivalent total heat input” vs. 71.74 “[no] lower heating rate to the package”
- **Certification by Analysis:** 71.73 provides parameters for certification by analysis while 71.74 requires physical testing

Note that 10CFR71.73(c)(4) specifies “hydrocarbon fuel/air fire” to denote the type of fuel to be used in the certification test but does not refer to a specific fuel. It defines the fire and surrounding ambient conditions, but leaves it up to the testing program to select the fuel to use as long as the required test conditions are met. Therefore, the more practical regulatory pool fire specification found in 10CFR71.73(c)(4) could serve as reference for future modifications or clarifications of the text provided in 10CFR71.74(a)(5).

SUMMARY AND COMMENTS

A comparison of large JP-4- and JP-8-fueled pool fires has been presented. The important differences in properties are the distillation temperature range and the vapor pressures of the two fuels. These differences make JP-8 harder to ignite and sustain combustion. The results herein indicate that JP-8 fires also require more time to become fully-developed. However, once a fire has become fully-developed, testing and numerical results indicate that the resulting JP-4- and JP-8-fueled pool fire environments are very similar. That is, numerical simulations and test data for 19 m diameter pools show the same trends: there is little difference in flame shapes, heights, and temperatures for the two fuels once the fully-developed burning stage has been reached. The somewhat smaller fuel vapor dome immediately above the pool surface associated with JP-8 pool fires translates to a possibly more severe regulatory fire environment than if JP-4 is used. This means that JP-8 fires may also provide slightly higher heat fluxes to the pool surface (or to objects or portion of objects in that vicinity) due to the reduced extent of the vapor dome.

All the information presented in this paper suggests that JP-4, JP-5, and JP-8 produce very similar pool fires and, therefore, very similar regulatory fire environments. Thus, from a technical and a practical standpoint, JP-8 is suggested as an alternate fuel to comply with the thermal environment implied in 10CFR71.74. In addition, the definition of the regulatory fire test specified in 10CFR71.73(c)(4) could serve as a guide for future modifications or clarifications of the text provided in 10CFR71.74(a)(5).

<u>Additional comment:</u> While 10CFR71.64(a)(1) [*Special requirements for plutonium air shipments*] points to 10CFR71.74, 10CFR71.55(f)(1)(iv) [*General requirements for fissile material packages / For fissile material package designs to be transported by air*] states “The thermal test in §71.73(c)(4), except that the duration of the test must be 60 minutes.” Note that 71.55(f) does not specify JP-4 or JP-5 and allows for the use of a “hydrocarbon fuel.” The authors of this paper do not know the reason for this difference, but in essence, 71.55(f) allows for the use of JP-8.

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