CRITICALITY SAFETY TRANSPORT INDEX CALCULATIONS FOR TRANSPORT CASK DESIGN OF EK-10 SPENT FUEL ELEMENTS

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SUMMARY

The results of the TNDSFP Code for thermo-nuclear design of spent fuel elements package are presented in this investigation. The code comprises both the transient analysis of a matched thermal-nuclear model to get the maximum clad surface temperature of the spent fuel elements during transportation and the nuclear criticality safety control index for the package design. The code is used to design a square arrayed dry cask of an assumed inner dimensions of 35cm.x35cm. to transport spent fuel elements. The data are taken from the EK-10 spent fuel elements. The results showed that the EK-10 spent fuel elements - after kept cooled in the storage pool for 3 months - can be safely transported - from nuclear and thermal points of view - in a square arrayed dry cask of inner dimensions 35cm.x35cm. containing up to 100 spent fuel elements (10x10 array) when stowed at a pitch of 3.5cm. In such case, the maximum clad surface temperature reaches 160.4 °C and the criticality safety transport index (TI) for such cask design equals 8.439 and this package can be safely transported up to 75 days transport time duration.

1. INTRODUCTION

The proper evaluation of the transport consequences for a cask used to transport the spent-fuel is of great importance in nuclear safety. This necessitates a proper evaluation for the cask design parameters. These parameters include thermal behavior of the spent fuel elements and nuclear criticality behavior of the package lattice during the transportation period. They heavily depend on the fuel elements operation historical data with the material content of the spent fuel and the corresponding percentage burn-up and the cooling time at which the spent fuel have been kept stored in the storage pool. The spent fuel elements - when removed from the reactor - are highly radioactive. They also contain some residual heat sources arising from fission product decay heat and decay heat of actinides. So they kept cooled for some time in a storage pool to remove some of this residual heat. However, during normal transportation conditions of a cask containing some spent fuel elements, the fission product decay heat source continues to dissipate - through the cask body - to the surrounding air. If the net amount of the heat generated in the spent fuel element and that radiated to it from other neighboring elements is great enough, its temperature will increase. Moreover, the long period of transportation may also cause heating up of the interior and/or clad surface temperatures possibly leading to an accident, such as rupturing or melting of the spent elements with a consequent dispersal of radioactivity or a possible formation of a critical configuration resulting from extensive temperatures within the cask structure or through its contents. So, the thermo- nuclear based design of a spent fuel transport cask is of great importance to safety in order to keep the criticality safety control transport index (TI) within the IAEA regulations(IAEA,1990) and to keep the maximum clad surface and fuel interior temperatures within their design safety limits considerations. Also, the cask cost must be taken into consideration during the design. An optimization is then essential between the cost and the thermo-nuclear design requirements.

TNDSFP MATHEMATICAL MODELS AND ITS NUMERICAL SOLUTIONS

The TNSDSFP code is a code for thermo-nuclear design of spent fuel elements package. Its models analysis incorporate the evaluation of the local instantaneous effective heat source generated in the spent- fuel element, Peff(t), arising from the different heat sources existing after fuel removal from the reactor. These sources are residual fission heat , fission products decay heat, and decay heat of actinides. It is derived through the solution of the space dependent reactor kinetic equation using the Rung-Kutta technique and is finally represented mathematically as(HENRY,1958):

$$P_{eff}(t) = P(t)\ [\ 1 - (\ {}_{j=1}\Sigma^{11}\ E_j^{\ h} + {}_{k=1}\Sigma^{2}\ E_k^{\ a}\ )] + {}_{j=1}\Sigma^{11}\ \lambda_j^{\ h}\ H_j(t) + {}_{k=1}\Sigma^{2}\ \lambda_k^{\ a}\ A_k(t) \qquad \text{......(1)}$$

where; E is the effective energy fraction, λ is the decay constant, H_j and A_k are the decay powers of fission products and of actinides respectively. The subscripts j , k are the fission product and the actinide decay heat group No. and the superscripts h , a are the fission product Number and the actinide No. This power generation source continues after the fission source stops due to the fission products decay. Its heat source varies with a rate depending on the reactor core operating history. So, the effective power generated in the spent fuel elements- after derived from the reactor - is reduced to:

$$P_{eff}(t) = {}_{j=1}\Sigma^{11}\ \lambda_j^{\ h}\ H_j(t) + {}_{k=1}\Sigma^{2}\ \lambda_k^{\ a}\ A_k(t) \qquad \text{..............................(2)}$$

The decay heat source is fitted to a polynomial of 11 exponentials. Also, the energy release from fission products decay is considered by including the important two radioactive actinides(U-239 and Np-239) that are produced by radioactive neutron capture in U-238. The differential equations of these heat sources are solved numerically using Adam's methods which is obtained by using the PECE method of the predictor-corrector(SHAMPINE,1975). This generated effective power reflects on the thermal behavior of the spent fuel elements in the cask. The heat transfer processes in the dry cask include radiant heat transfer besides the heat transfer by thermal conduction. The radiant heat transfer in the spent-fuel dry cask is found to be the dominant heat dissipation process for the resulting temperature distribution(AHMED,1996). The calculations were made using the net radiation method. So, the radiant temperature of any spent fuel element located at (i,j) is thus given by(MCADMS,1985):

$$T^4_{i,j} = (1/(\varepsilon_{i,j}\ .\sigma)).[\ P_{i,j}^{\ o} - (\ 1 - \varepsilon_{i,j})\ .\ {}_{n=1}\Sigma^{N}\ P_n^{\ o}.\ F_{i,j-n}\ ] \qquad \text{..................(3)}$$

where; $\varepsilon_{i,j}$ is the emissivity of the clad wall material and σ is the Stefan Boatsman's constant. The $F_{i,j-n}$ are the weighted configuration factors between the spent fuel rod located at i,j and each of its n surrounding neighbor spent rods. The output power of the spent fuel rod located at i,j ($P_{i,j}^{o}$) equals to the effective power - given by Eq.(2)- multiplied by the total transport time ΔT_{tr}, i.e.;

$$P_{i,j}^{\circ} = P_{eff}(t).\ \Delta T_{tr.} \qquad \text{.................................(4)}$$

It is assumed in the model that all the spent fuel elements present in the cask have equal percentage burn-up. Consequently, they have all an equal output powers. In other words, the output power of each of the n spent rods neighboring and surrounding the i,j spent rod equals the output power of the i,j spent rod (i.e. $\mathbf{P_{i,j}^{\circ} = P_n^{\circ}}$).

In the TNDSFP code, the fuel heat transfer model calculates the internal temperature distribution within the fuel solid material considering the effects of both the axial conduction and the temperature-dependence of fuel thermal conductivity. The time dependent heat flow equation is used(OZISIK,1980):

$$\nabla.\ (k\ \nabla\ T_{i,j}) + P_{i,j} = \rho\ C_p\ (\partial T_{i,j}/\ \partial t) \qquad \text{.............................(5)}$$

and solved in three-dimensional cylindrical geometry, which is then reduced to linear partial differential equation using Kirchoff's transformation and then solved numerically using a combination of the orthogonal collocation technique(FINLEYSON,1972) and finite difference technique(SMITH,1971). For the heat conduction through the clad, the transient energy balance for lumped clad in finite difference form is used and then transformed to get the implicit time derivative and the explicit axial conduction using Kirchoff's transformation. Implicit temperatures are then evaluated using the truncated Taylor Series(LIENHARD,1981). The three equations governing the heat conduction through fuel interior to clad surface are combined together to yield the following Tensor equation for the transformed temperatures:

$$S\ \theta = E \qquad \text{.....................................(6)}$$

which is solved by iterative Gauss-Seidel procedure(OZISIK,1980) with the iteration become terminated when convergence is satisfied. Thus solution of θ operator vector is obtained and the implicit temperatures are evaluated using the truncated Taylor series:

$$T_{n,z,t+1} = T_{n,z,t} + [\ \theta_{\ n,z,t+1} - G(\ T_{n,z}t\ ))\ /\ G'(\ T_{\ n,z,t}\ )] \qquad \text{..........................(7)}$$

where; $T_{n,z,t}$ is the temperature at any radial node n within the fuel and the clad materials, at any axial level z and at any time, and G is the inverse function of either the spent fuel or the clad materials and G' is its derivative with respect to temperature. The solution of Eq.(7) at the clad outer surface node gives the transient axial clad outer surface temperature due to conduction. Therefore, this value should super imposed on the fuel element surface temperature due to radiation (given by Eq.(3)) to get the total clad outer surface temperature due to both radiation and conduction.

Based on the amount of fissile radio-nuclides present in the spent fuel elements (U^{235}, U^{233} and Plutonium) and the percentage burn-up, the criticality safety control transport index (TI) is calculated according to the general NRC license approval and restricted to the fissile class III shipment with radio-nuclides are not uniformly distributed(10CFR,1995). Also, according to the IAEA regulations, the license is issued if TI < 10(IAEA,1990).

RESULTS AND DISCUSSIONS

Figures(1) to (6) show the results obtained when applying the TNDSFP code to design a cask used to transport some EK-10 spent fuel elements such that the transportation is maintained safe from thermal and nuclear aspects during the period of transportation, and the cask follows the IAEA and the NRC license requirements. The EK-10 type nuclear fuel is the nuclear fuel of the Egyptian first research reactor (ET-RR-1). It is made of uranium oxide dispersed in magnesium matrix, cladded with aluminum and enriched by 10% U^{235} when the fuel is fresh. It is delivered to the reactor in the form of fuel baskets, each contains 16 fuel rods. The fuel rods are cylindrically shaped of outer diameter 10 mm. and 50 cm. active length and the aluminum clad tube thickness is 1.5 mm. The fuel rods are assembled in 4x4 square lattice form with pitch 1.7 cm.. The fuel mass is depleted by the reactor operation. The fuel maximum percentage burnup is 25%(EAEA,1993). In the present investigation, it is assumed that all the fuel elements required to be transported have the same percentage burn-up of 22.47%.

Figure(1) shows the variation of the nuclear criticality safety index during transportation versus the no. of the transported spent fuel elements. As shown in the figure, increasing the no. of the transported spent rods to be stowed in a square arrayed form in the cask leads to increase the cask TI value. This is referred to the increase in the fissile material content as the fuel burnup increase. However, for the 35cm.x35cm. cask inner dimensions to be stowed with EK-10 spent fuel rods in a 10x10 array form, the TI is found to be 8.4 which is less than both the IAEA and the NRC transportation license requirements. In Fig.(2), the variation of the clad surface thermal behavior within that cask versus the square arrayed lattice pitch is illustrated. As shown in figure, the maximum clad surface temperature increases as the lattice pitch decreases. This is referred to increasing the effect of thermal radiation heat source term as the lattice pitch goes smaller. However, within the present cask dimensions, the clad surface temperature does not exceed 160.4°C which lies within the thermal safety limits considerations. Figure(3) illustrates the thermo-nuclear behavior for the EK-10 spent fuel elements when transported in dry cask of inner dimensions 35cm.x35cm. which also ascertains the results of Figs.(2) and (3).

The nuclear and thermo-nuclear design criteria charts for the square arrayed dry cask to transport EK-10 spent fuel elements with the effect of the transportation time on these parameters are illustrated in three dimensional pattern in Figs. (4),(5)m and (6). It is worthy noting that the presented results are taken at 90 days storage cooling time. Generally, as illustrated in the figures, the proposed dry cask of inner dimensions of 35cm.x35cm. can be safely stowed with (3x3), or (4x4), or (5x5),.....up to (10x10) square arrayed of EK-10 spent fuel elements assembled in a square lattice with a corresponding pitch of 10 cm., 8.75 cm., 7 cm.,.....up to 3.5 cm. and can also be safely transported up to 75 days transport time duration. In such case, the corresponding nuclear criticality control index (TI) varies from 0.2946 to 8.43949 (i.e. $TI < 10$) which means that these cask arrangements can get the transportation license according to both IAEA and NRC regulations. Moreover, as shown from the figures the corresponding maximum clad surface temperatures are far below the clad (aluminum) melting point.

From the cost analysis point of view for the present studied spent fuel cask arrangements for the proposed dry cask of inner dimensions 35cm.x35cm., it is recommended to stow the

EK-10 spent fuel elements with the (10x10) square arrayed arrangement since the maximum clad surface temperature does not exceed 160.4°C which lies within the thermal safety limits considerations and the TI value is 8.439 which is less than both the IAEA and the NRC transportation license requirements.

CONCLUSIONS

1. The TNDSFP code is used to design a cask to transport some EK-10 spent fuel elements such that the transportation is maintained safe from thermal and nuclear aspects during the total period of transportation, and the cask follows the IAEA and the NRC license requirements.
2. The proposed dry cask of inner dimensions of 35cm.x35cm. can be safely stowed with (3x3), or (4x4), or (5x5),.....up to (10x10) square arrayed of EK-10 spent fuel elements assembled in a square lattice with a corresponding pitch of 10 cm., 8.75 cm., 7 cm.,.....up to 3.5 cm. and can also be safely transported up to 75 days transport time. In such case, the corresponding nuclear criticality control index (TI) varies from 0.2946 to 8.43949 (i.e. TI < 10) which means that these cask arrangements can get the transportation license according to both IAEA and NRC regulations. Moreover, as shown from the figures the corresponding maximum clad surface temperatures are far below the clad (aluminum) melting point.
3. From the cost analysis point of view for the present studied spent fuel cask arrangements for the proposed dry cask of inner dimensions 35cm.x35cm., it is recommended to stow the EK-10 spent fuel elements with the (10x10) square arrayed arrangement since the maximum clad surface temperature does not exceed 160.4°C which lies within the thermal safety limits considerations and the TI value is 8.4 which is less than both the IAEA and the NRC transportation license requirements.

5. REFERENCES

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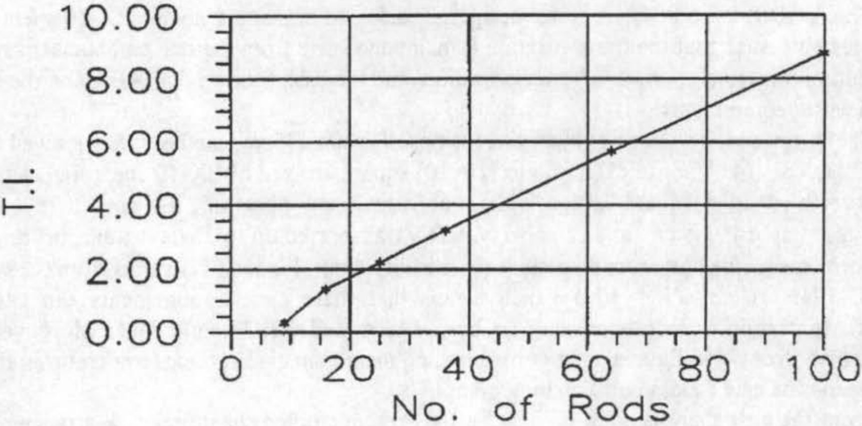

Fig. (1) The Variation of The Nuclear Criticality Safety Control Index During Transportation (T. I.) Versus The No. Of The Transported Spent Fuel Rods

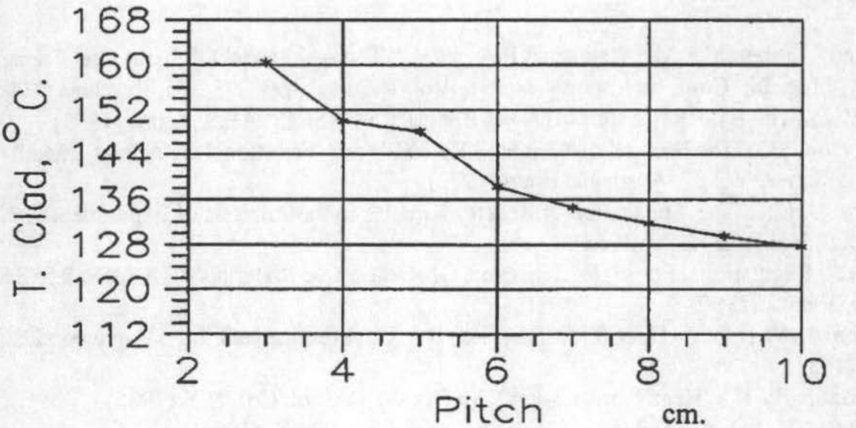

Fig. (2) The Variation of The Maximum Clad Surface Temperature Versus The Lattice Pitch of The Square Arrayed Design Cask

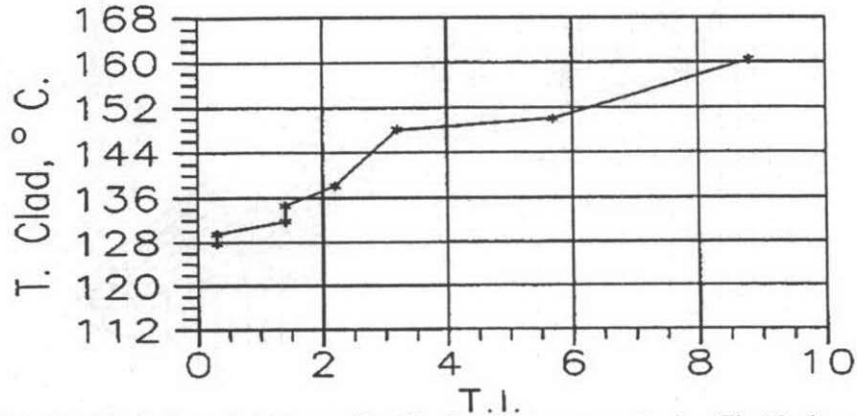

Fig.(3) The Variation of Maximum Clad Surface Temperature Against The Nuclear Criticality Transport Index (TI) for The Square Arrayed Design Transport Cask

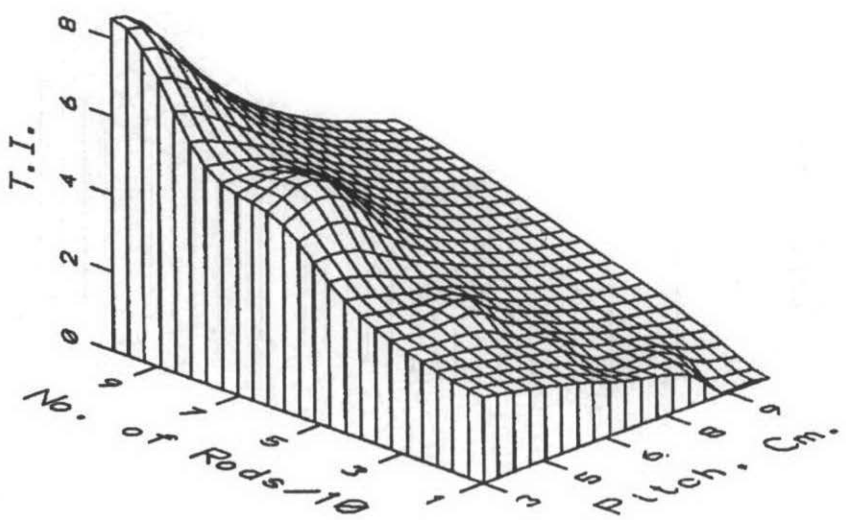

Fig.(4) Nuclear Design Criteria Charts For The Square Arrayed Cask To Transport EK-10 Spent Fuel Elements

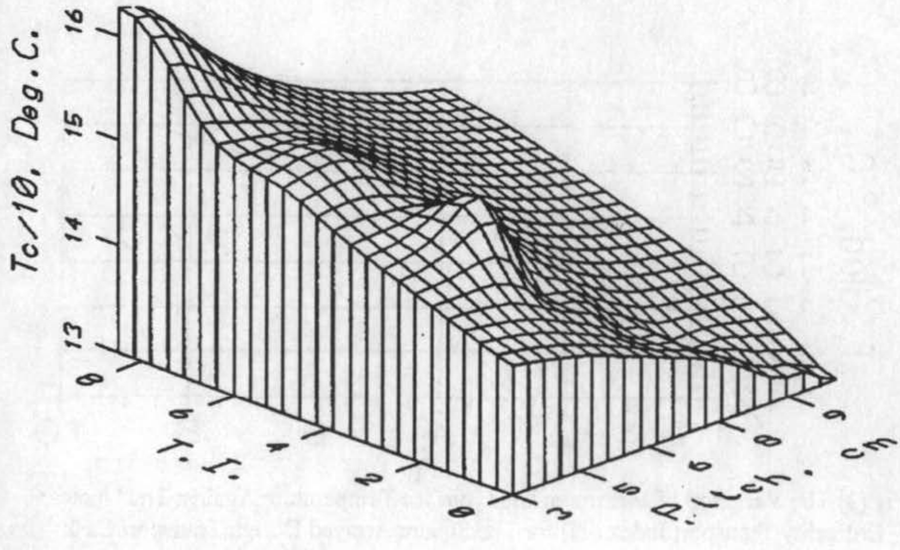

Fig.(5) Thermo-Nuclear Design Criteria Charts For The Square Arrayed Cask To Transport EK-10 Spent Fuel Elements

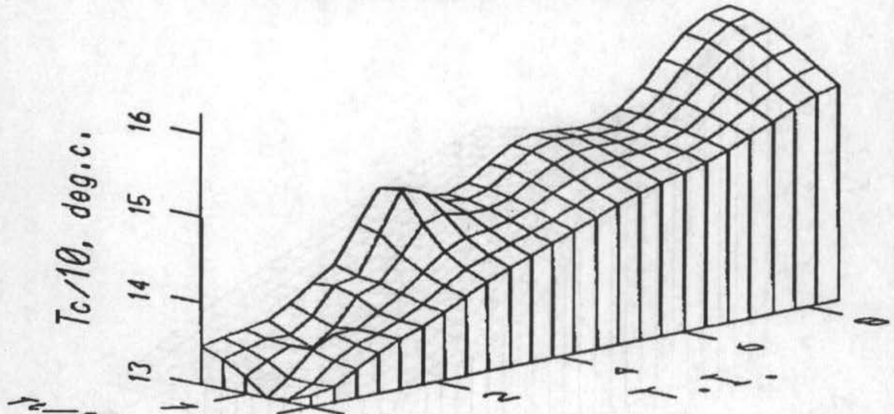

Fig.(6) Effect of Transportation Time (T_t) on The Thermo-Nuclear Design Parameters of The Square Arrayed Cask (35cm.X35 cm.) To Transport EK-10 Spent Fuel Elements