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DEVELOPMENT OF COMPUTER PROGRAM TO MODEL CYLINDRICAL INCIDENT DISCRETE EMISSIVE RADIATION (CINDER) FROM POOL FIRES

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GENESIS OF CONCEPT

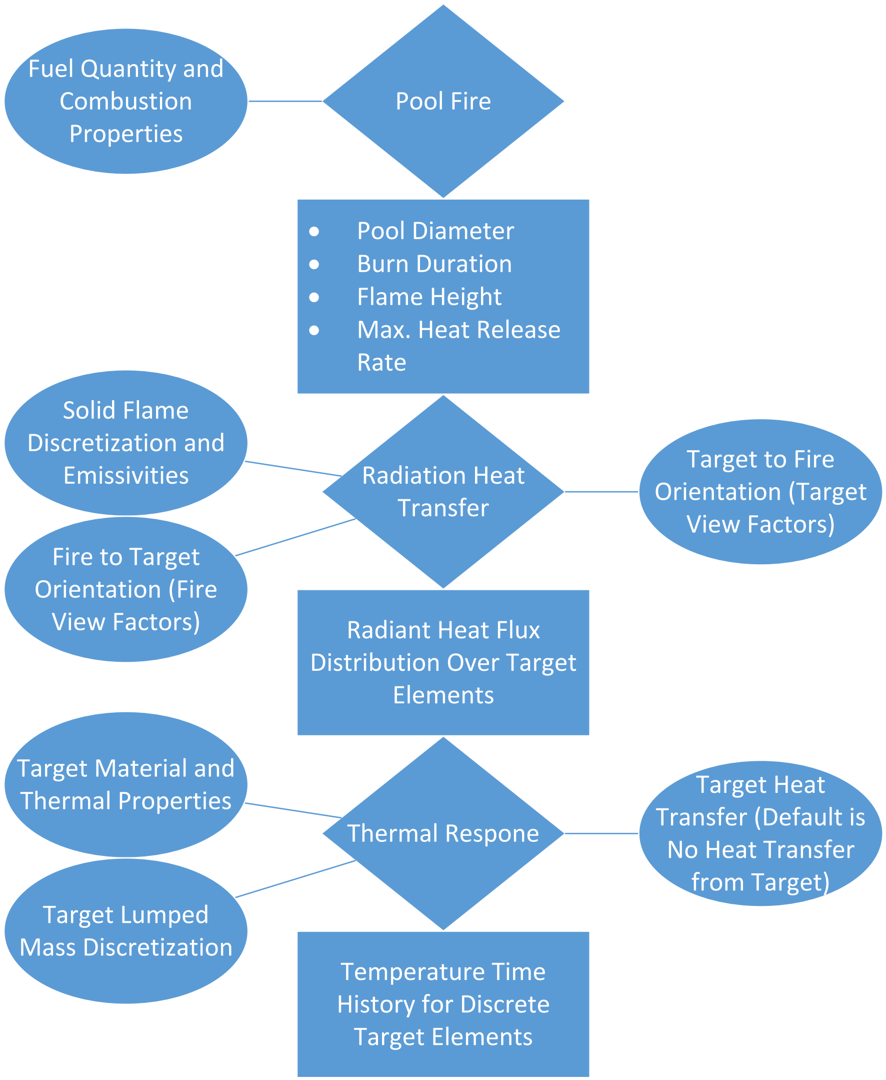
IDEA GENERATED BY JOURNAL ARTICLE

- Quiel, Spencer E., Yokoyama, Takayuki, Bregman, Lynne S., Mueller, Kevin A., and Marjanishvili, Shalva M. (2015). A Streamlined Framework for Calculating the Response of Steel-Supported Bridges to Open-Air Tanker Truck Fires. *Fire Safety Journal, 73*, 63-75.
- Journal homepage: www.Elsevier.com/locate/firesaf
- Simplified tool to evaluate the response of bridges to open-air hydrocarbon pool fire resulting from a tanker truck crash
- Similar approach could be adopted for Fire PRA scenarios that involve exposed structural steel

PRESENTATION TOPICS

- Modeling Approach
- Modeling Geometry
- Program Flowchart
- Algorithmic Approach
- Existing Modeling Approach
- Sample Problem
- Benchmarking of Results
- Target Temperature Response
- Summary

MODELING APPROACH



MODELING GEOMETRY

GRAPHIC REPRESENTATION

- Cylindrical INcident Discrete Emissive Radiation => *CINDER*
- Oil pool fire is represented by cylindrical flame divided into discrete radiation elements and target represented by one-dimensional geometry divided into discrete lumped-mass elements

$$\dot{q}_j'' = \sum_{i=1}^{n} E_i \frac{A_i \cos\theta_i \cos\theta_j}{\pi R_{i\to j}^2}$$

$\dot{q}_j''$ => Radiation Heat Flux Imparted to Target Node j

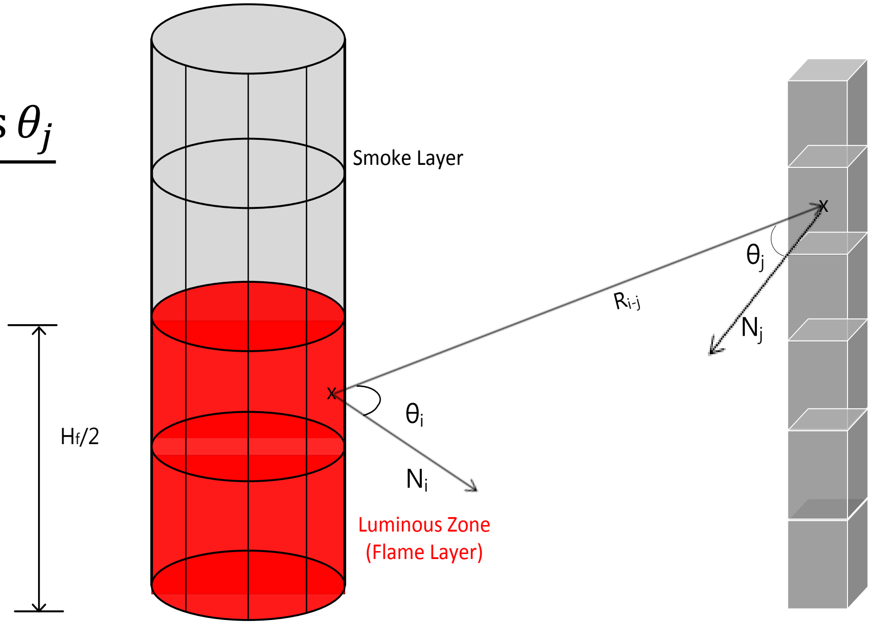
E_i => Emissive Power of Flame Element i

A_i => Area of Flame Element i

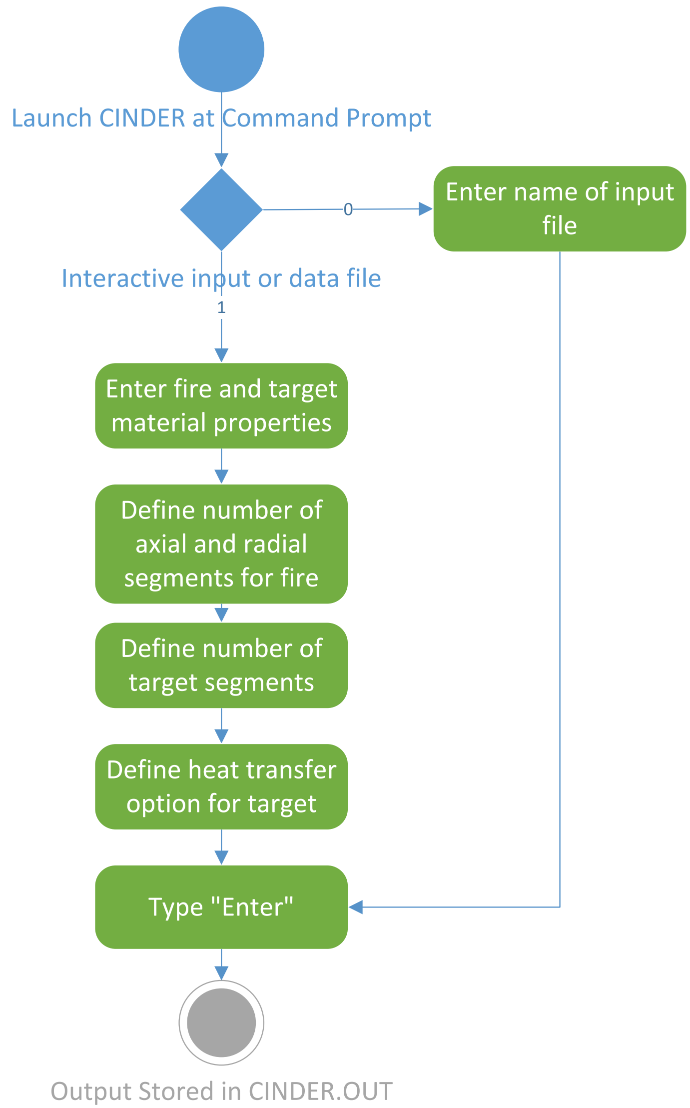
θ_i => Angle between Fire Element Normal and Distance Vector

θ_j => Angle between Target Normal and Distance Vector

$R_{i\to j}$ => Distance between Flame Element and Target Node



PROGRAM FLOWCHART



ALGORITHMIC APPROACH

- Target temperatures calculated using iterative time steps
- Allows for heat transfer from target to surroundings, if desired

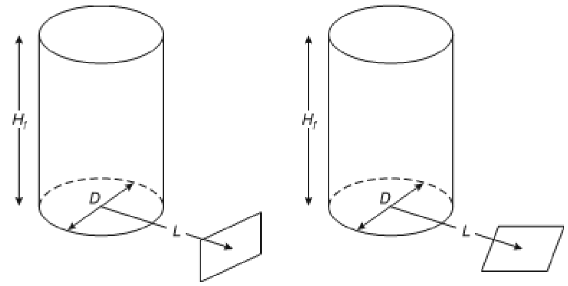
```
C CALCULATE THE TARGET NODAL TEMPERATURES AT EACH TIME STEP
      J = 0
      T = 0
      DO 20 T = 1, TTOTAL
        DO 21 J = 1, TLDIV
          TEMPJ(0,T) = TAMB
          TEMPJ(TLDIV+1,T) = TAMB
          IF (T .EQ. 1) THEN
            TEMPJ(J,T) = TAMB
            QDJM1J(J,T) = 0.0
            QDJJP1(J,T) = 0.0
            QDOTOUT(J,T) = 0.0
          ELSE
          IF (TGTHTR .EQ. 0) THEN
          TEMPJ(J,T)=TEMPJ(J,T-1)+(1./(TA*TL*TRHO*CT))*
     &    (TL*PTEJ(J)*QDOTIN(J))
          ELSE
          QDJM1J(J,T-1)=(THCOND(TEMPJ((J-1),(T-1)))+
     &    THCOND(TEMPJ(J,(T-1))))
     &    *(TEMPJ((J-1),(T-1))-TEMPJ(J,(T-1)))*TA/(2.*TL)
          QDJJP1(J,T-1)=(THCOND(TEMPJ(J,(T-1)))+
     &    THCOND(TEMPJ((J+1),(T-1))))
     &    *(TEMPJ(J,T-1)-TEMPJ((J+1),(T-1)))*TA/(2.*TL)
          QDOTOUT(J,(T-1))=(PTT-PTEJ(J))*TL*(HAMB*(TEMPJ(J,(T-1))-TAMB)+
     &    SB*ES*((TEMPJ(J,(T-1))+273.15)**4.-(TAMB+273.15)**4.))
C CALCULATE THE TEMPERATURE FOR NEXT TIME STEP
          TEMPJ(J,T)=TEMPJ(J,T-1)+(1./(TA*TL*TRHO*CT))*
     &    (TL*PTEJ(J)*QDOTIN(J)-QDOTOUT(J,T-1)+QDJM1J(J,T-1)-
     &    QDJJP1(J,T-1))
          END IF
          END IF
   21   CONTINUE
   20 CONTINUE
```

EXISTING MODELING APPROACH

ACCEPTED METHODS

- Shokri and Beyler detailed methods using shape factor algebra
  - Section 5.3.2 of NUREG-1805
  - Section 66 of SFPE Handbook, 5th Edition

Fig. 66.19 Cylindrical flame-shape configuration factor geometry for vertical and horizontal targets at ground level



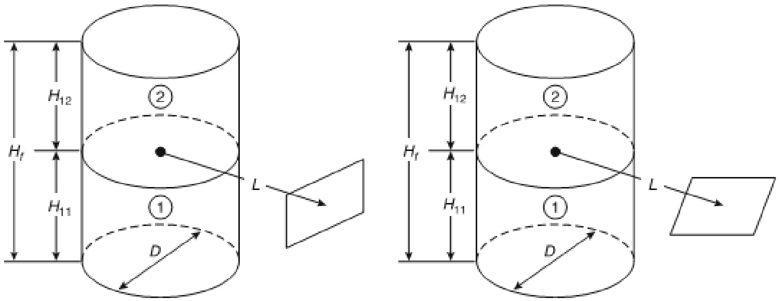
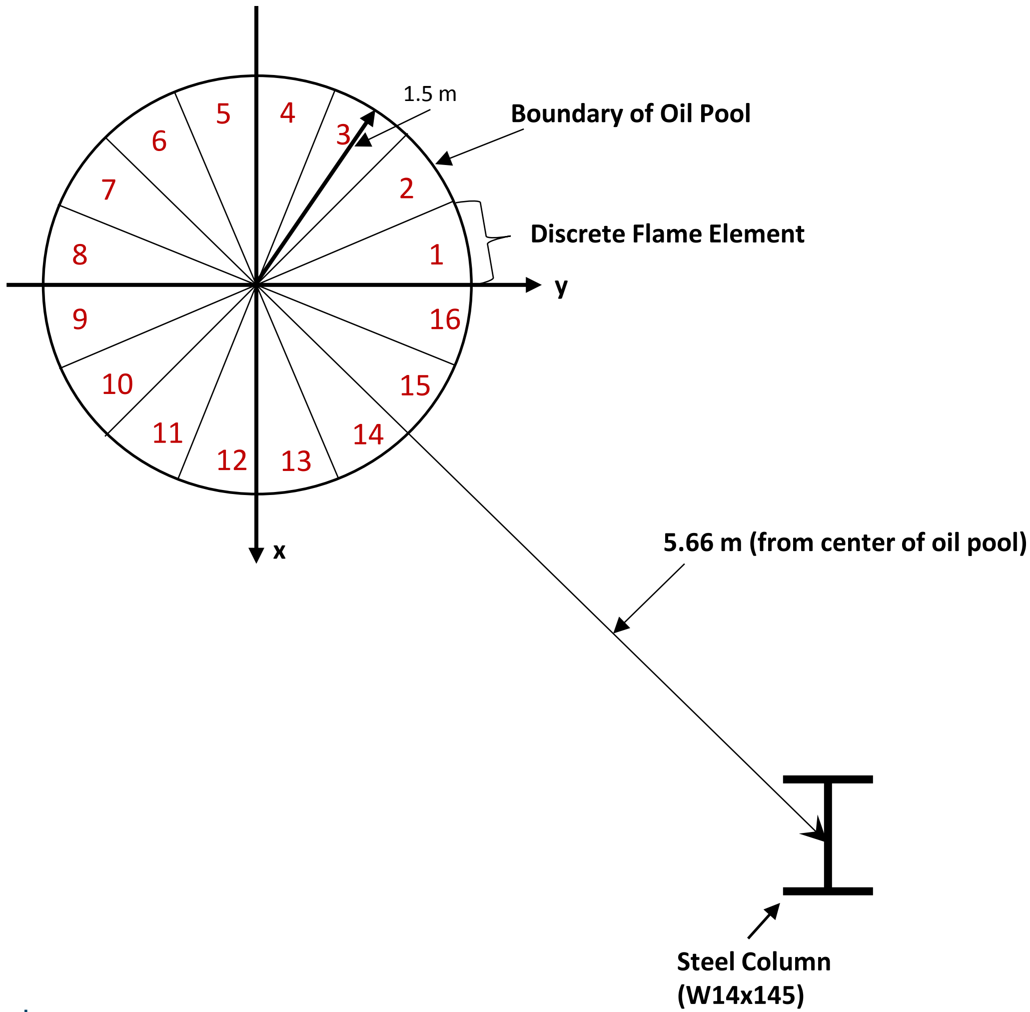


Fig. 66.20 Two-cylinder representations of the configuration factor for target above ground level

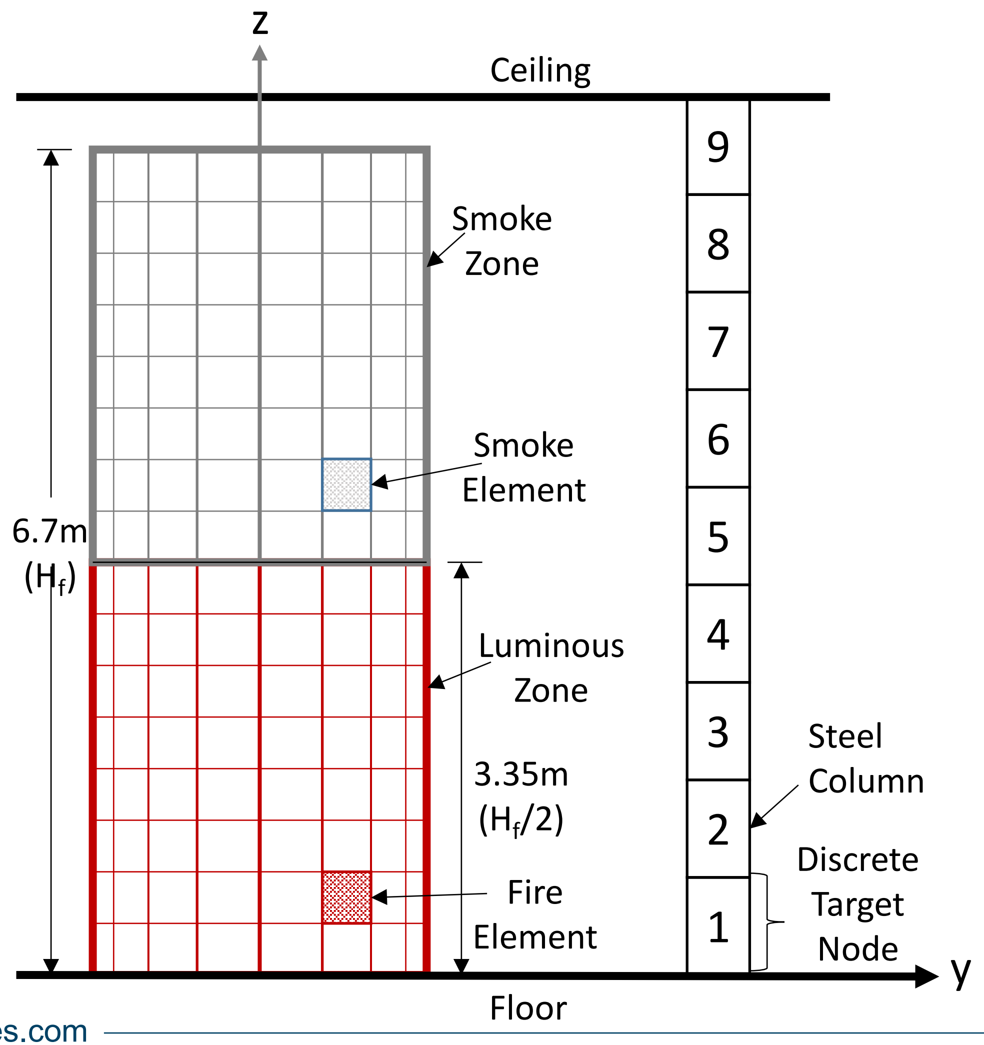
SAMPLE PROBLEM

TOP VIEW OF POOL FIRE NEAR STEEL COLUMN



SAMPLE PROBLEM

SIDE VIEW OF POOL FIRE NEAR STEEL COLUMN



BENCHMARKING OF RESULTS

COMPARISON OF METHODS

- Heat fluxes calculated by CINDER at mid-point of target closely match those using Shokri and Beyler method (within 2%):
- CINDER results:

```
RADIATION HEAT FLUX AT TARGET ELEMENT     1 IS  0.11794E+05 W/M^2
RADIATION HEAT FLUX AT TARGET ELEMENT     2 IS  0.13466E+05 W/M^2
RADIATION HEAT FLUX AT TARGET ELEMENT     3 IS  0.14301E+05 W/M^2
RADIATION HEAT FLUX AT TARGET ELEMENT     4 IS  0.14204E+05 W/M^2
RADIATION HEAT FLUX AT TARGET ELEMENT     5 IS  0.13315E+05 W/M^2
RADIATION HEAT FLUX AT TARGET ELEMENT     6 IS  0.11908E+05 W/M^2
RADIATION HEAT FLUX AT TARGET ELEMENT     7 IS  0.10240E+05 W/M^2
RADIATION HEAT FLUX AT TARGET ELEMENT     8 IS  0.84831E+04 W/M^2
RADIATION HEAT FLUX AT TARGET ELEMENT     9 IS  0.67552E+04 W/M^2
```

← 13.3 kW/m^2

- Shokri and Beyler approximations:

$Q_{smoke} := 4.019$ incident radiant heat flux from smoke layer, kW/m^2

$Q_{flame} = 9.547$ incident radiant heat flux from luminous layer, kW/m^2

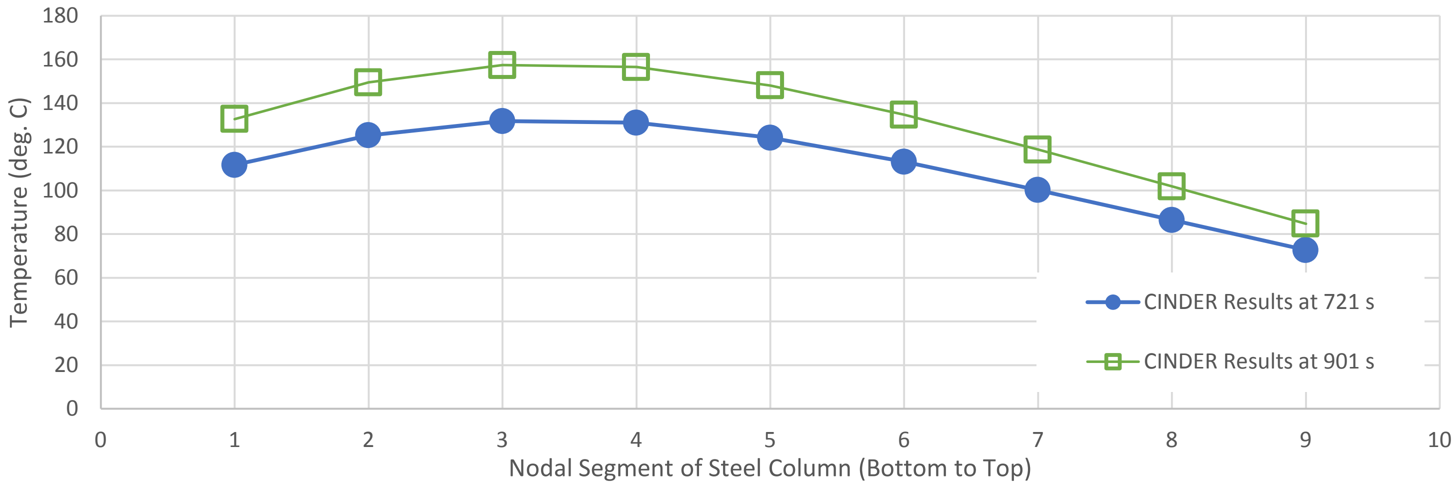
$Q_{total} := Q_{flame} + Q_{smoke}$

$Q_{total} = 13.566$ total incident radiant heat flux, kW/m^2

TARGET TEMPERATURE RESPONSE

- Temperatures calculated at time steps for each target element:

```
TEMPERATURE AT TARGET NODE     1 IS          111.6801 DEG C AT TIME STEP   721 SECONDS
TEMPERATURE AT TARGET NODE     2 IS          125.2242 DEG C AT TIME STEP   721 SECONDS
TEMPERATURE AT TARGET NODE     3 IS          131.7116 DEG C AT TIME STEP   721 SECONDS
TEMPERATURE AT TARGET NODE     4 IS          130.9622 DEG C AT TIME STEP   721 SECONDS
TEMPERATURE AT TARGET NODE     5 IS          124.0772 DEG C AT TIME STEP   721 SECONDS
TEMPERATURE AT TARGET NODE     6 IS          113.1454 DEG C AT TIME STEP   721 SECONDS
TEMPERATURE AT TARGET NODE     7 IS          100.1593 DEG C AT TIME STEP   721 SECONDS
TEMPERATURE AT TARGET NODE     8 IS           86.4565 DEG C AT TIME STEP   721 SECONDS
TEMPERATURE AT TARGET NODE     9 IS           72.6605 DEG C AT TIME STEP   721 SECONDS
TEMPERATURE AT TARGET NODE     1 IS          132.6679 DEG C AT TIME STEP   901 SECONDS
TEMPERATURE AT TARGET NODE     2 IS          149.4322 DEG C AT TIME STEP   901 SECONDS
TEMPERATURE AT TARGET NODE     3 IS          157.3805 DEG C AT TIME STEP   901 SECONDS
TEMPERATURE AT TARGET NODE     4 IS          156.4650 DEG C AT TIME STEP   901 SECONDS
TEMPERATURE AT TARGET NODE     5 IS          148.0335 DEG C AT TIME STEP   901 SECONDS
TEMPERATURE AT TARGET NODE     6 IS          134.6330 DEG C AT TIME STEP   901 SECONDS
TEMPERATURE AT TARGET NODE     7 IS          118.6964 DEG C AT TIME STEP   901 SECONDS
TEMPERATURE AT TARGET NODE     8 IS          101.8610 DEG C AT TIME STEP   901 SECONDS
TEMPERATURE AT TARGET NODE     9 IS           84.8069 DEG C AT TIME STEP   901 SECONDS
```



SUMMARY

CODE LIMITATIONS

- CINDER generates a warning message if the calculated flame height exceeds the ceiling height, which could result in upper portions of the target being directly exposed to the flame
- For portions of the target that are located directly above the fire plume, nodal temperatures are estimated using the plume temperature correlation found in NUREG-1805
- The current version of the code only accommodates one target represented by a single line element per input file
- Estimating target temperatures for compartments in which a hot gas layer develops is beyond the current capabilities of CINDER

SUMMARY

STATUS OF CINDER PROJECT

- Functional version is now available for demonstration purposes
- Adopts fundamental equations referenced in NUREG-1805 and found in SFPE Handbook
- Functional capabilities undergoing in-house review for future research initiative to investigate possible use as a fire modeling tool
- Possible integration with Fire PRA Workbook that is currently undergoing development by JENSEN HUGHES

QUESTIONS?

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