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Title

Topical report for the food Irradiator of Paina Hawaii

Objective

Objective of the calculation is to determine the critical velocity and drag required to pull up the nuclear material that may be released inside the irradiator pool in the event of a natural disaster like tsunami and hurricane.

Personnel

J Durham is the principal investigator. The environmental hazard calculations were done under the guidance of J Stamatakos.

Date: 11/3/2006

Definition of different quantities used in the calculation process

Reynolds Number = $\frac{\rho v d}{\mu}$

Drag Coefficient = $C_D = \frac{F_D}{\frac{1}{2} A \rho v^2}$

The drag force is written as $F_D = C_D \frac{1}{2} \rho v^2 A$

The symbols mean

A=Projected Area
V=velocity magnitude
C_D=Drag Coefficient
F_D=Drag Force
μ=Fluid Viscosity
ρ=Fluid density
d=equivalent diameter or length scale
m=mass of the radioactive material
g=gravitational constant (9.81 m/s^2)

Values of constants

The radioactive materials

The radioactive material (Cobalt-60) comes in two forms and each of them were used in the calculation and described below

Equivalent Sphere

The shape of the radioactive materials (whether pellet or slugs) are cylindrical. In the present calculation the shape is assumed to be cylindrical. But an equivalent spherical shape was also assumed where the volume of the equivalent sphere is equal to volume (and hence mass) of the cylindrical material. This is done in order to ensure the orientation of the cylindrical body does not affect the calculation procedure. As will be discussed later that the drag force induced on the cylinder or sphere is dependent on the shape and orientation of the body. The flow facing the edges of the cylinder is likely to be create different effect and drag from the flow facing the sides of a cylinder. During a catastrophic scenario, it is difficult to predict, if the cylindrical object will remain in a definite orientation with respect to the direction of gravity. It may spin or assume any random orientation, making it very difficult to calculate accurate drag over the body. The equivalent sphere (that has the same mass and volume of the original cylinder) is conceptualized as a representative body of the radioactive mass and could have only one orientation with respect to gravity and flow. It is also assumed that the equivalent cylinder will provide a conservative estimate of drag.

Note added by Kaushik Das on 12.27.06 for clarification of units in the following calculations

All the calculations are performed in SI units. So
Length dimensions (radius r, height h etc) = meters (unless explicitly mentioned in otherwise)
Density (ρ) in kg/m^3
Acceleration due to gravity (g)=9.81 m/s^2

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a) Typical slugs

Diameter (d)=6.35 mm
Height (h)=12.7 mm

Volume of the cylinder$=\pi d^2h/4=\pi\times(6.35\times 6.35\times 12.7)/4$ mm^3
$= 402.19\ mm^3 = 4.02199\times 10^{-7}\ m^3$

Density of the material=8.9 g/cm^3 =8900 kg/m^3
Mass of a single slug=volume × density=8900 $kg/m^3\times 4.02199\times 10^{-7}\ m^3$
$=3.579\times 10^{-3}$ kg
So the weight of a single typical slug W=mg,
Where, g= gravitational acceleration = 9.81 m/s^2
$W=3.579\times 10^{-3}\times 9.81=0.035$ N.

For an equivalent sphere of same volume,

$4/3\times\pi r^3=4.02199\times 10^{-7}$
Where, r=equivalent radius
So, $r=4.579\times 10^{-3}$ meters
So equivalent diameter $d=9.15\times 10^{-3}$ m

b) Minimum Mass (Pellets)

Diameter (d)=0.76 mm
Height (h)=0.76 mm

Volume of the cylinder=$\pi d^2 h/4 = \pi \times (0.76 \times 0.76 \times 0.76)/4$ mm^3
$= 0.345$ mm^3 $=3.45 \times 10^{-10}$ m^3

Density of the material=8.9 g/cm^3 =8900 kg/m^3
Mass of a single slug=volume × density=8900 kg/m^3 × 3.45×10^{-10} m^3
$=3.0705 \times 10^{-6}$ kg
So the weight of a single typical slug W=mg,
Where, g= gravitational acceleration = 9.81 m/s^2
W=$3.0705 \times 10^{-6} \times 9.81 = 3.01216 \times 10^{-5}$ N.

For an equivalent sphere of same volume,

$4/3 \times \pi r^3 = 3.45 \times 10^{-10}$
Where, r=equivalent radius
So, r=4.35×10^{-4} meters
So equivalent diameter d=8.702×10^{-4} m

Properties of Saltwater (Sea water) used in the calculation

Assumed Temperature of sea water during Tsunami or Hurricane = 50^0 F.
All other properties are calculated at that temperature level;

Water density (ρ)= 1027 kg/m^3 9Approximaterly 64.17 lb/ft^3)
Water viscosity (μ)=1.4 cp (CentiPoise) = 1.4 ×10^{-3} Pa S (Pascal Seconds)

Date: 11/5/2006

Assumptions made in the calculation procedure:

1. Temperature is assumed to be constant at 50^0 F that is at 10^0 C.
2. Steady state assumption is made
3. Calculations are performed in a 2-D plane and assumed symmetry of the irradiator pool
4. The irradiator pool has a rectangular cross section with a L/D (length to depth ratio) of 1.575. In the present calculation we will assume L/D=1.0 for a conservative estimate and availability of experimental as well as validated simulation data.

5. The density and viscosity remains constant (They are assumed to be the function of temperature only; which is very reasonable in the temperature range considered and water will be in liquid state).
6. The irradiator pool is modeled as a 2-D pool with shear driven cavity flow under accident scenario.
7. The flow calculation is done assuming the presence of gravity and drag force. All other forces are neglected as their magnitude is considerably small compared to these forces. Essentially the calculation focuses on the balance between weight and drag.
8. The objects inside the irradiator pool are not considered into the calculation. This is a conservative assumption because presence of any other object in the pool will only impede the motion of the radioactive substance and obstruct hauling of the pellets/slugs. So the presence of structures in the pool is beneficial in case of a disastrous event and an empty pool with only salt water is a conservative assumption.

Problem Statement and Modeling technique

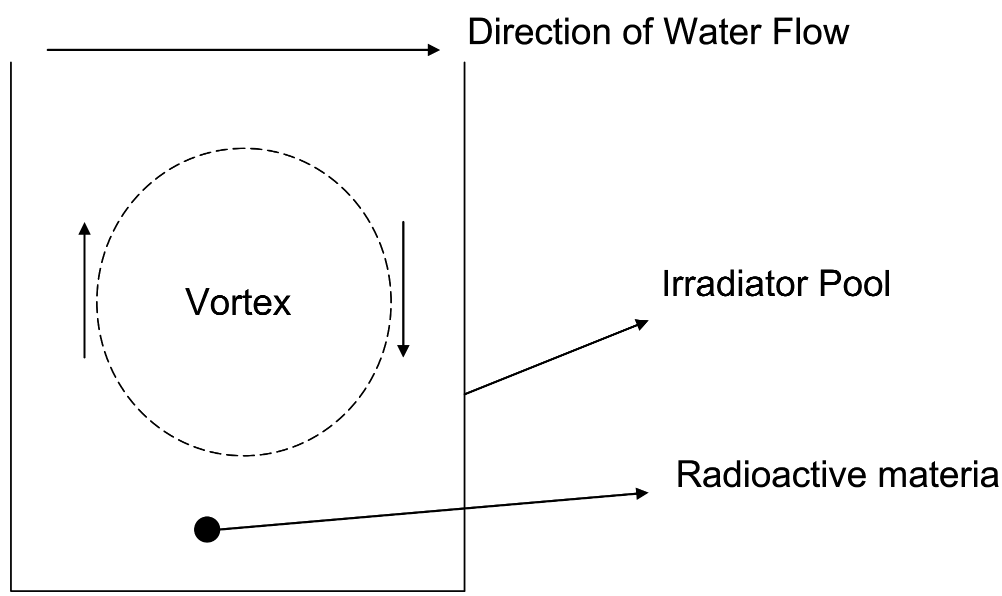

Figure 1: Schematic of the Problem

The schematic of the problem considered is shown below. It is assumed that a disastrous event like tsunami and hurricane will cause flooding of the irradiator chamber which in turn will cause a water flow over the irradiator pool. This flow of water will create a shear force at the top of the pool which in turn will induce a vortex as shown in Figure 1. The direction of the vortex depends on the direction of the water flow on the top of the pool.

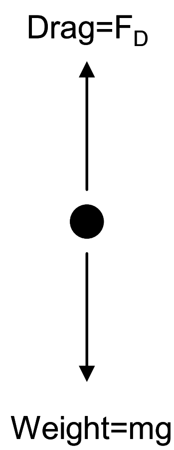

Figure 2: Force acting on the sphere

Date: 11/6/2006

The vortical motion of the fluid will induce drag on the body which will either try to push it up towards the free surface or pull it down along with gravity downwards, depending upon the location of the body with respect to the vortex. For cases,

(i) Where the body is pulled downward, no calculation needs to be performed, because the material collected at the bottom of the pool poses no hazard and could be easily collected later.

(ii) Where the body is pulled upward, poses a threat as the radioactive material may reach the surface and float around.

Hence, the whole problem has essentially three steps

(a) Determine the limiting circumstance, when the radioactive body starts moving upwards due to the effect of vortex induced drag. Under limiting circumstance, F_D (Drag) = mg (Weight). If F_D (Drag) $<$ mg (Weight), then the body will drown and will not float. If F_D (Drag) $>$ mg (Weight), then the body will move upwards. So it needs to be determined at which local velocity, the drag equals weight.

(b) Determining the shear velocity that would create such a drag. In short, the velocity sweeping the cavity opening needs to be determined that would create enough drag to pull up the body.

(c) Determine the flooding velocity inside the pool room that a natural event like tsunami or hurricane could cause. It is assumed that the shear velocity of the cavity opening will only be a fraction of the water velocity created by such natural disasters, as the source and the poll is secured inside a building which will act as a barrier and considerably reduce the original velocity.

Date: 11/7/2006

Subproblem-1 (Calculation of critical drag and velocity)

In this section, the critical velocity and drag will be determined, that makes the radioactive material to float.

Under limiting circumstances (the significance of the symbols are described before)

$F_D=mg$

$F_D=C_D\times\frac{1}{2} A\rho V^2$

Hence, $mg= C_D\times\frac{1}{2} A\rho V^2$ (1)

Now $C_D=f(Re)$
$V=f(Re)$

So the unknown quantities C_D and V, both depend on Reynolds number.

C_D could be determined from the experimental curved depending upon the shape of the body and the Reynolds number. The velocity V could also be determined using the same procedure.

Equation (1) can be expressed in the form

$C_DV^2 = mg/\frac{1}{2} A\rho$ (2)

The left hand side of equation (2) represents all the unknowns and is a function of Reynolds number.
The right hand side is known, as all the quantities that compose it are available either from design data or are natural constants.
The solution procedure is iterative. The algorithm of the solution is given below

(1) Guess a Reynolds number (Re)
(2) Determine the corresponding value of C_D from the chart.
(3) Put that value of C_D in equation (2) and find the value of V
(4) Determine the Reynolds number using the calculated V as $Re=\frac{\rho vd}{\mu}$

(5) See, whether the newly calculated Re is different from the guessed Re in step 1.
(6) If they are very different, then repeat the whole process using the new Re
(7) If they are within reasonable value, that is the acceptable Re and the velocity is the acceptable critical value that is enough to start a upward motion of the body.

1. Calculation of smaller pellets

1.1 Assuming cylindrical pellets

Assumptions are

(i) During the event, pellets will have the cylinder axis perpendicular to the vertical direction. This is natural from stability consideration as it is less likely that the cylinder will be oriented vertically if released from the fuel chamber.
(ii) The flow will impinge on the flat circular bottom surface of the body.
(iii) Drag on the curve side walls due to any cross flow is neglected as the magnitude will be smaller compared to the vertical drag.

The C_D values are calculated from the chart 9.13 of page 441 (Introduction to fluid Mechanics; Robert W Fox, Alan T. McDonald and Philip J. Pritchard, Sixth Edition, John Wiley and Sons, Inc). The figure shows the variation of C_D with different Reynolds number in log-log scale.

Area=$0.76\times0.76\times10^{-6}$ m^2

$C_DV^2 = mg/½ A\rho$ (from equation 2)
$C_DV^2 = 3.01216 \times 10^{-5}/(½ \times 1027 \times 5.776\times10^{-7})$
$C_DV^2 = 0.102532$ (1.1)

Guess-1: Re=1.0
Corresponding C_D=10.0
So from equation (1.1) V=0.10125

Reynolds number= $\frac{\rho vd}{\mu}$ =1027 kg/m^3 ×0.10125 (m/s)×0.76 (mm)/1.4 (centipoises)=56.45

Note added by Kaushik Das on 12.27.06 for clarification of units in the following calculations

Though all the units are in SI, for calculation of Reynolds number= $\frac{\rho vd}{\mu}$, the units of d and μ are kept in mm and centipose respectively. This is done because both have a conversion factor of 10^{-3} for converting them to SI and cancels out from the numerator and the denominator. So in essence it does not matter in this calculation whether they are kept in cgs or in SI units.

Guess-2: Re=56.46

Corresponding C_D=2.0

So from equation (1.1) V=0.2264

Reynolds number= $\frac{\rho vd}{\mu}$ =1027×0.2264×0.76/1.4=126.22

Guess-3 Re=126.22

Corresponding C_D=1.8

So from equation (1.1) V=0.23866

Reynolds number= $\frac{\rho vd}{\mu}$ =1027×0.23866×0.76/1.4=133.06

The change in velocity is reasonably small and change in Reynolds number is not high. With a change in Reynolds number less than 50, there is very little possibility of change in drag coefficient. So this is the acceptable value of velocity and Reynolds number.

*1.2 **Assuming standing cylinder***

The standing cylinder calculation was not carried out because that it was less likely that the cylinder axis will be along the vertical line in case of release. Moreover, any C_D value for standing cylinder was not available, which was accepted as standard.

1.3 Assuming equivalent spherical pellets

Assumptions are

(i) The actual cylindrical pellet is replaced with a sphere with equal volume and mass.
(ii) The effect of cross flow and resultant drag is neglected.
(iii) The flow direction from bottom to top will be considered for drag calculation.
(iv) The effective area is the cross sectional area of the sphere.

Equivalent radius=0.43×10^{-3}
Equivalent diameter=0.86×10^{-3}

$$C_D V^2 = mg/\tfrac{1}{2} A\rho \quad \text{(from equation 2)}$$
$$C_D V^2 = 3.01216 \times 10^{-5}/(\tfrac{1}{2} \times 1027\times\pi \times (0.43\times10^{-3})^2)$$
$$C_D V^2 = 0.1 \qquad (1.2)$$

Guess-1: Re=100.0 (Using the guess from the previous calculation)
Corresponding C_D=1.0
So from equation (1.2) V=0.316227
Reynolds number=$\dfrac{\rho v d}{\mu}$=1027×0.316227×0.868/1.4=201.0

Guess-2: Re=201.0 (Using the guess from the previous calculation)
Corresponding C_D=0.9
So from equation (1.2) V=0.333
Reynolds number=$\dfrac{\rho v d}{\mu}$=1027×0.333×0.868/1.4=210.125

No appreciable change in Re and velocity. So the final velocity=201.0 and Reynolds number=201.00

Date: 11/8/2006

2. Calculation of larger slugs

1.1 Assuming cylindrical slugs

The same assumptions that were made in connection with smaller pellets are also made here. The assumptions are restated here

Assumptions are

(i) During the event, pellets will have the cylinder axis perpendicular to the vertical direction. This is natural from stability consideration as it is less likely that the cylinder will be oriented vertically if released from the fuel chamber.
(ii) The flow will impinge on the flat circular bottom surface of the body.
(iii) Drag on the curve side walls due to any cross flow is neglected as the magnitude will be smaller compared to the vertical drag.

The C_D values are calculated from the chart 9.13 of page 441 (Introduction to fluid Mechanics; Robert W Fox, Alan T. McDonald and Philip J. Pritchard, Sixth Edition, John Wiley and Sons, Inc). The figure shows the variation of C_D with different Reynolds number in log-log scale.

Area=$6.35\times12.70\times10^{-6}$ m^2

$$C_DV^2 = mg/\tfrac{1}{2}A\rho \quad \text{(from equation 2)}$$
$$C_DV^2 = 0.035/(\tfrac{1}{2}\times 1027\times6.35\times12.7\times10^{-6})$$
$$C_DV^2 = 0.84518 \qquad (2.1)$$

Guess-1: Re=1.0

Corresponding C_D=10.0
So from equation (2.1) V=0.29
Reynolds number=$\dfrac{\rho v d}{\mu}$=1027×0.29×6.35/1.4=1350.0

Guess-2: Re=1350

Corresponding C_D=1.5
So from equation (2.1) V=0.75
Reynolds number=$\dfrac{\rho v d}{\mu}$=1027×0.75×6.35/1.4=3493.6

Guess-3: Re=3493.6

Corresponding C_D=1.0
So from equation (2.1) V=0.919
Reynolds number=$\dfrac{\rho v d}{\mu}$=1027×0.919×6.35/1.4=4280.866

Guess-4: Re=4280.0

Corresponding C_D=0.95
So from equation (2.1) V=0.943

Reynolds number=$\frac{\rho v d}{\mu}$=1027×0.943×6.35/1.4=4393.68

With further change in Reynolds number, there will not be any appreciable change in C_D and velocity V. So the final calculated velocity is 0.943 m/s and Reynolds number of 4393.68.

1.2 Assuming equivalent spherical slugs

The same assumptions that were made in connection with smaller pellets are also made here. The assumptions are restated here

Assumptions are

(i) The actual cylindrical pellet is replaced with a sphere with equal volume and mass.
(ii) The effect of cross flow and resultant drag is neglected.
(iii) The flow direction from bottom to top will be considered for drag calculation.
(iv) The effective area is the cross sectional area of the sphere.

Equivalent radius=4.579×10^{-3}
Equivalent diameter=9.15×10^{-3}

C_DV^2 = mg/½ Aρ   (from equation 2)
$C_DV^2 = 0.035/(½ \times 1027\times\pi \times (4.579\times10^{-3})^2)$
$C_DV^2 = 1.0347$ (2.2)

Guess-1: Re=100.0 (Using the guess from the previous calculation)
Corresponding C_D=1.0
So from equation (2.2) V=1.017

Reynolds number=$\frac{\rho v d}{\mu}$=1027×1.017×9.15/1.4=6826.28

Guess-2: Re=6826.28 (Using the guess from the previous calculation)
Corresponding C_D=0.5
So from equation (2.2) V=1.4385

Reynolds number=$\frac{\rho v d}{\mu}$=1027×1.4385×9.15/1.4=9655.46

Guess-3: Re=9655.5 (Using the guess from the previous calculation)

Corresponding C_D=0.55
So from equation (2.2) V=1.37
Reynolds number= $\frac{\rho v d}{\mu}$ =1027×1.37×9.15/1.4=9195

With further change in Reynolds number, there will not be any appreciable change in C_D and velocity V. So the final calculated velocity is 1.37 m/s and Reynolds number of 9195.0

Table 1 Synopsis of Velocity and Drag Calculation

Large Slugs			
Dimension (in mm)	Type	Critical Reynolds number	Critical Velocity (m/s)
Diameter=6.35 mm Height=12.7 mm	Cylindrical	4393.0	0.943
Equivalent diameter=9.15 mm	Spherical	9425	1.404
Small Pellets			
Diameter=0.76 mm Height=0.76 mm	Cylindrical	133.06	0.238
Equivalent diameter=0.8699 mm	Spherical	200	0.336

Of all the calculations done in this section, the equivalent sphere of the large slug is the most representative one as (i) usage of large slugs are preferred as they provide the necessary radiation and (ii) the random orientation of the cylinder will likely result in a configuration best represented by a equivalent sphere.

Date: 11/9/2006

Subproblem-2 (Tank Flow Analysis)

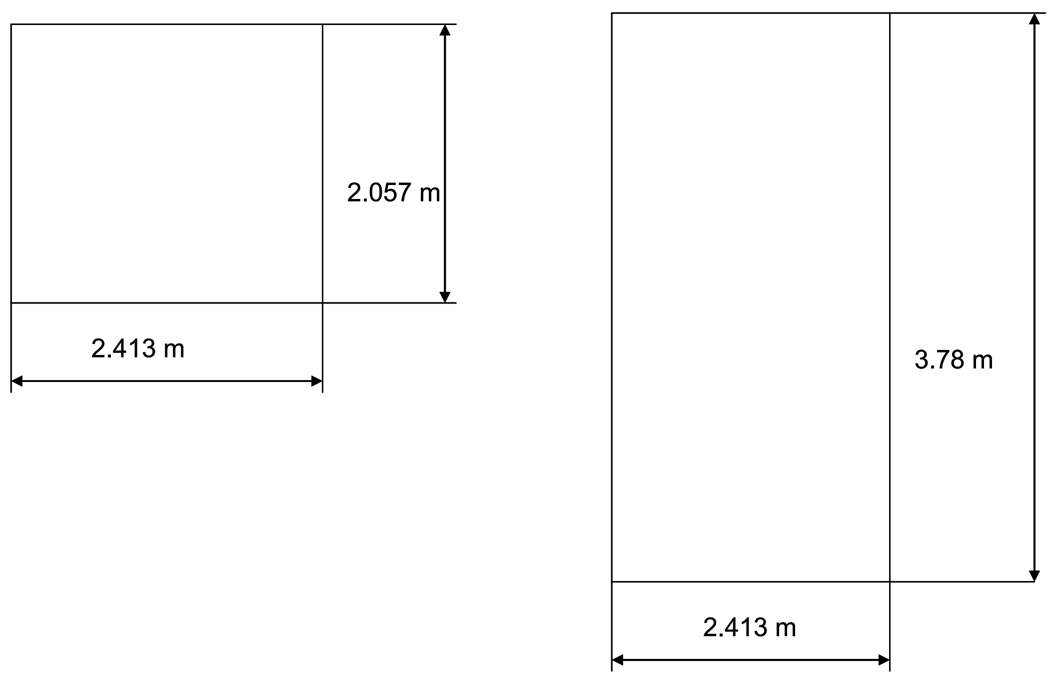

Figure 3 Approximate dimension of the irradiator pool

Correction of Tank Dimension on 12.20.2006 by Kaushik Das-----The height of the tank will be 5.4 meters instead of 3.78 meters as shown in the diagram

As mentioned earlier that the irradiator pool will be modeled as a shear driven cavity. The approximate dimension of the pool is shown in Fig 3. The length to depth ratio is 1.57. But the poll will be modeled as square one with length to depth ratio of 1.0. This is a conservative estimate because the actual pool with L/D > 1.0 is technically known as deep cavity and the bottom of the pool is less likely to be influenced by the shear at the pool opening. The present analysis will adopt the results of a cavity with L/D=1.0, where the bottom of the poll is influenced by the shear velocity. The reason for this approximation is the availability of a vast pool of technical data related to L/D=1 cavities describing the flow field and the vortex. These results are available in open literature and have been validated with experimental observations. Some of the results are numerical simulations and are established as benchmark solution for comparison, validation and verification. The flow within shear driven or lid driven cavity is a well researched area and the flow physics is very well understood. The numerical simulation data by Ghia et al (Ghia, ghia and Shin (1982), "High Reynolds number solutions for incompressible flow using the Navier-Stokes equation and a multigrid method", Journal of Computational Physics, Vol-48. pp-387-411) is one of the well established results and accepted in the technical community as a benchmark to validate experimental and numerical results. The present calculation will use the results in this paper to compute the shear velocity.

The references related to shear driven cavity flow are listed here

(i) Ghia, Ghia and Shin (1982), "High Reynolds Number Solutions for Incompressible Flow Using the Navier-Stokes Equation and a Multigrid Method", Journal of Computational Physics, Vol-48. pp-387-411

(ii) Bozeman and Dalton (1973), "Numerical Study of Viscous Flow in Cavity", Journal of Computational Physics, Vol-12, pp. 348-363.

(iii) Erturk, Corke and Gokcol (2005) "Numerical Solutions of 2-D Steady Incompressible Driven Flow at High Reynolds Numbers", International Journal for Numerical Methods in Fluids, Vol-48, pp. 747-774

Correction for the references by Kaushik Das on 12.27.2006

(i) Ghia U, K.N. Ghia and C.T. Shin (1982), "High Reynolds Number Solutions for Incompressible Flow Using the Navier-Stokes Equation and a Multigrid Method", Journal of Computational Physics, Vol-48(3). pp-387-411

(ii) Bozeman J andC. Dalton (1973), "Numerical Study of Viscous Flow in Cavity", Journal of Computational Physics, Vol-12(3), pp. 348-363.

(iii) Erturk E, T.C Corke and C. Gokcol (2005) "Numerical Solutions of 2-D Steady Incompressible Driven Flow at High Reynolds Numbers", International Journal for Numerical Methods in Fluids, Vol-48, pp. 747-774

(iv) Fox, R.W., A.T. McDonald, and P.J. Pritchard. "Introduction to Fluid Mechanics." 6th Edition. Hoboken, New Jersey: John Wiley and Sons, Inc. 2006.

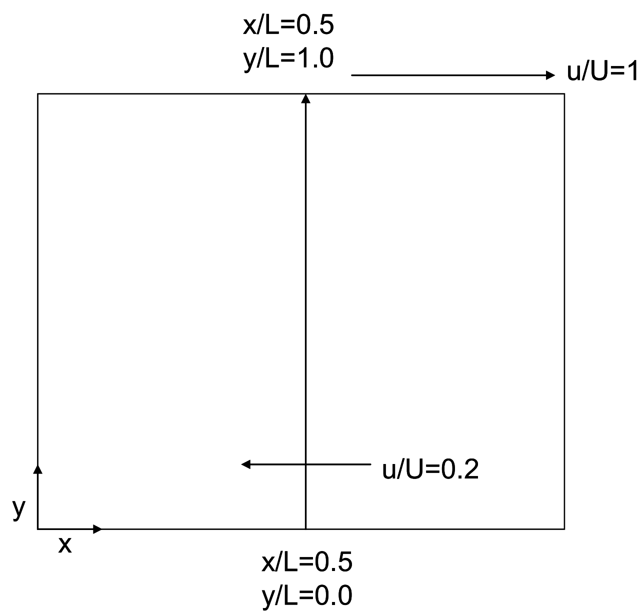

Figure 4 Approximate solution of the cavity problem

The literature related to the flow in shear driven cavity indicates that the maximum velocity attainable in the lower portion of the cavity is given by u/U=0.2. The direction of velocity in the lower part of the pool will be in the opposite direction to that of the shear velocity in the pool opening due to the direction of the vortex as explained in Figure 1.0. The velocity gradually decreases to 0.0 in the core of the vortex and subsequently increases to the shear velocity at the opening. The details of the flow physics and the velocity distributions are available in the listed reference.

The radioactive materials are likely to be in the lower portion of the cavity as evident from the design of the irradiator pool and location of the plenum. The velocity acting on the body is u and the radio of the local velocity u to the shear velocity U could have a maximum value of 0.2. We will assume this maximum value as this provides us the most conservative estimate of the shear velocity. Any velocity ratio below the maximum value will result in higher value of shear velocity and less likely to be produced by any natural disaster and flooding.

The critical local velocity u is calculated in the previous section. We need to know, what shear velocity could produce this critical local velocity. As discussed previously, any velocity smaller than this critical value will have no effect from safety consideration and any value higher than this will cause the radioactive material to float and cause safety concerns.

For determining the critical shear velocity from the critical local velocity the ratio u/U=0.2 will be used. The tabulated values for different material and body are given below.

Table 2. Shear velocity calculated

Large Slugs		
	u (calculated Previously) (m/s)	U (shear velocity=0.2×u (m/s)
Cylindrical	0.943	4.715
Spherical (equivalent)	1.409	7.045
Small Pellet		
Cylindrical	0.238	1.19
Spherical (equivalent)	0.336	1.68

Subproblem-3 (Velocity Produced by Natural Events)

This section will analyze the water velocity that could be produced by natural events and if that is sufficient for the critical velocity. It is assumed that the tsunami will produce a higher velocity of water than a hurricane and hence the typical velocity parameters of a tsunami wave are used for assessment.

Typical wave velocity at shore = 30 mph=13.4112 m/s
Typical wave height at shore (approximately 100 ft) =30 m

Though the wave velocity at the shore is higher compared to all the critical velocities in Table 1, it should be noted that the irradiator pool will be housed within a building and the wave will have to essentially destroy a number of barriers including the walls of the building before it creates an effective velocity over the pool. Hence the velocity of water at the pool opening will be a very small fraction of the original wave velocity.

Date: 11/11/2006

Summary

A fluid dynamic calculation was carried out to estimate the effect of natural events like tsunami or hurricane on the irradiator nuclear materials. It was assumed that in such a occurrence, if the irradiator plenum and source holder structure fails, the radioactive cobalt-60 will be released inside the pool. An assessment was made about the velocity magnitude that would be required to pull the radioactive material body onto the poll opening. It was determined that under limiting conditions, the weight of a pellet/slug has to be the same as the drag induced by the fluid. The drag force is dependent on a number of factors including effective area and the orientation of the body with respect to the fluid. It was estimated that the cylindrical body can be oriented randomly in the fluid, calculations were performed on an equivalent sphere. The equivalent sphere had the same volume, mass and weight of the original body. The pool was modeled as a two-dimensional cavity with a shear flow inducing a vortical motion in it. This vortical motion is in turn responsible for inducing drag on the radioactive body. It was determined that for an equivalent cylinder, a vertical velocity of 1.4 m/s is required to induce a drag force sufficient to lift the body. It was determined from the theory of shear driven cavity flow that a shear velocity of 7.05 m/s is necessary to produce this upward velocity. The

tsunami velocity at the shore is around 13 m/s and it will have only a fraction of this value as it reaches the irradiator pool due to the presence of buildings and other barriers as irradiator structure.

It should be emphasized that the assumptions are highly conservative. Also the calculations are carried out for a single slug or pellet. In case the slugs are bound together, there will be an increase in weight without much increase in drag resulting in drowning of the material. Also the assumption of shallow cavity as opposed to deep cavity reduced the shear velocity magnitude required to pull the material upwards. In the present calculation, the presence of debris and other structures inside the pool is completely neglected. The presence of these things in the pool will result in a very slow moving fluid, which is very less likely to achieve the velocity required to pull the material body upwards.

Entered by J. Durham on 12-08-06:

After consideration of the results of the above calculations, it was decided that assuming the Co-60 source assemblies would be destroyed was not a credible accident. It was decided that an entire source assembly should be modeled instead of a single slug or pellet. The source assembly is to be modeled as an equivalent sphere with the same mass, density, and volume as a source assembly. It is not necessary to repeat the entire calculation; instead, the calculation for the slug is to be modified to account for the difference in mass between a slug (0.4 g) and the mass of an entire source assembly. The ratio of the new shear critical velocity to the slug critical velocity is calculated by taking the square root of the ratio of the mass of the source assembly (m_{SA}) to the mass of the slug (m_S). The new shear velocity is calculated using the same methodology. In mathematical terms,

$$\frac{u_{SA}}{u_S} = \sqrt{\frac{m_{SA}}{m_S}}$$

and

$$\frac{V_{SA}}{V_S} = \sqrt{\frac{m_{SA}}{m_S}}$$

A source assembly consists of the source material made of Co-60, a stainless steel inner capsule, and a stainless steel outer capsule. Both capsules consist of a tube with two end caps. The length of the source material is 422 mm, the diameter is 6.35 mm, and the density is 8.9 g/cm^3. The volume of the source material (v_{SM}) is

$v_{SM} = \pi\ (6.35\ \text{mm})^2 \times 422\ \text{mm}/4 = 13400\ \text{mm}^3 = 13.4\ \text{cm}^3$

and the mass (m_{SM}) is

m_{SM} = 13.4 cm^3 (8.9 g/cm^3) = 119 g.

The inner capsule has an inner diameter of 6.35 mm, a wall thickness of 0.6 mm, and a length of 449 mm. The density of stainless steel is assumed to be 7.6 g/cm^3. The volume of the inner capsule (v_{IC}) is

$v_{IC} = \pi\ [(7.55\ \text{mm})^2-(6.35\ \text{mm})^2] \times 448\ \text{mm}/4 + 2 \times \pi\ (7.55\ \text{mm})^2 \times 0.6\ \text{mm}/4 = 5930\ \text{mm}^3$

v_{IC} = 5.93 cm^3

and the mass (m_{IC}) is

m_{IC} = 5.9 cm^3 (7.6 g/cm^3) = 45 g.

The outer capsule has an outer diameter of 12.7 mm, a wall thickness of 0.7 mm, and a length of 455 mm. The volume of the outer capsule (v_{OC}) is

$v_{OC} = \pi\ [(12.7\ \text{mm})^2- (11.3\ \text{mm})^2] \times 455\ \text{mm}/4 + 2 \times \pi\ (12.7\ \text{mm})^2 \times 0.7\ \text{mm}/4 = 12200\ \text{mm}^3$

v_{OC} = 12.2 cm^3

and the mass (m_{OC}) is

m_{OC} = 12.2 cm^3 (7.6 g/cm^3) = 93 g.

The total mass of a source assembly is

$m_{SA} = m_{SM} + m_{IC} + m_{OC}$ = 119 g + 45 g + 93 g = 257 g.

$$\frac{u_{SA}}{u_S} = \sqrt{\frac{257g}{0.4g}} = 25$$

similarly,

$$\frac{V_{SA}}{V_S} = 25$$

Using the previously calculated values for the critical velocity and the shear velocity, the new value for the source assembly critical velocity is

u_{SA} = 35 m/s (79 mph)

and the source assembly shear velocity is

V_{SA} = 118 m/s (265 mph).

These velocities are significantly larger than those produced by tsunamis on land.

Calculation Verification, Comments and Corrections 12-22-2006 by Kaushik Das

The calculation verification of the entire source assembly is done here. It is mentioned in the last section that a credible accident will not involve breaching the source assembly and release of the nuclear material (slugs or pellets of Cobolt-60) and the source will remain intact. The new set of calculation focuses on the behavior of the whole source assembly instead of isolated nuclear material.

The subsequent calculation will focus on the hydrodynamic behavior of the cylindrical source assembly (with dimension of the outer cylinder as mentioned in the previous calculation) in presence of a vortex generated by a shear velocity. Also in this calculation a fresh approach have been adopted to correlate the vertically upward velocity needed to float the body and the shear velocity needed to generate. The basis of the new correlation or approach is based on references listed below and other observation or CFD simulations available in open literature. Detailed of this approach will be discussed later in this chapter.

Approach-1 (Using ratio relations as adopted in the previous section to cross check the calculation)

$$C_D V^2 = \frac{mg}{\frac{1}{2}\rho A}$$

We may assume that the C_D remains constant for a wide range of Reynolds number, both for a spherical and cylindrical body. So the proportionality relation becomes as follows

$$\frac{V_1^2}{V_2^2} = \frac{m_1}{m_2} \times \frac{A_2}{A_1}$$

The subscript 1 designates the whole fuel assembly and 2 designates the individual sources (slugs).

m_1=257 gm (calculated in the previous section as m_{SA} or the mass of the whole source assembly)
m_2=35.3 gm (mass of an individual pellet)

Similarly

A_1= cross sectional area of the whole source assembly = 12.7 mm × 144 mm
A_2= cross sectional area of an individual pellet = 6.35 mm × 12.7 mm

$$\frac{V_1^2}{V_2^2} = \frac{257}{35.3} \times \frac{6.35 \times 12.7}{12.7 \times 455}$$ (We have assumed cylindrical bodies here)

Correction made by Kaushik Das on 1/11/07. The area dimension of A_1 was changed from 12.7 ×144 to 12.7 × 455; The cylinder length was previously taken as 144 mm and corrected to 455 mm to reflect the actual dimension. The length 144 mm is actually the hypotenuse of the rectangular cross sectional area of the cylinder face.

$$\frac{V_1^2}{V_2^2} = 0.1$$

Correction made by Kaushik Das on 1/11/07. suggested by reviewer D Basu that $\frac{V_1^2}{V_2^2} = 0.1$ ***and not 0.32 as was previously entered***

$$V_1 = 0.32 \times V_2$$

So as V_2=0.943 m/s (The units of V_1 and V_2 should be the same irrespective of the units of mass and area)

V_1=0.3 m/s

Hence for cylindrical bodies the velocity to lift the whole source assembly will be 0.3 m/s

The calculation repeated for an equivalent sphere.

Diameter of the source assembly = 12.7 mm
Length of the source assembly=455 mm

Hence the external area of the outer cylinder of the whole source assembly=

$$\frac{\pi}{4}(12.7\text{mm})^2 \times (455\text{mm}) = 57637.97\text{mm}^3 = 57.637\text{cm}^3 = 5.7637 \times 10^{-5}\text{m}^3$$

For an equivalent sphere the volume of the sphere should be equal to the volume of the cylinder; Hence

$$\frac{4}{3}\pi r^3 = 5.7637 \times 10^{-5}\text{m}^3$$

Hence the equivalent sphere radius = $r = 0.0239\text{m} = 2.39\text{cm}$
And the equivalent diameter=d= $d = 0.047925\text{m} = 4.792\text{cm}$

So the calculation will be

$$\frac{V_1^2}{V_2^2} = \frac{257}{35.3} \times \frac{\pi(4.579 \times 10^{-3})^2}{\pi(0.0239)^2}$$

$$\frac{V_1^2}{V_2^2} = 0.26$$

$$V_1 = \sqrt{0.26} \times V_2$$

As V_2 for the equivalent sphere case previously was 1.409 m/s

Hence V_1=0.71845

These estimates are far less than what had been calculated in the previous section. However a rigorous calculation is performed in the next section to check the validity of the assumption that drag coefficient remains the same and to see how much the velocity changes for a cylindrical body to a spherical body

Synopsis of the calculation is listed in the table below with the critical parameters mentioned

Type of Object	Current dimension	Previous dimension	Previous velocity	Current velocity
Cylindrical	Diameter=12.7 mm Length=455 mm	Diameter=12.7 mm Length=35 mm	0.943 m/s	0.3 m/s
Equivalent Sphere	Equivalent diameter=47.925 mm	Equivalent diameter=9.15 mm	1.409 m/s	0.71845 m/s

(Correction made to this table to reflect the accurate dimension and result as mentioned in the previous section; Correction by Kaushik Das on 1/11/07 and suggested by J Durham)

Approach-2 (Using the rigorous fluid dynamic approach of iteration and repeated drag calculation)

(i) <u>Considering equivalent sphere</u>

The logic of considering a equivalent sphere was discussed previously.
As calculated in the previous section
Diameter of the equivalent sphere is 47.925 mm

The relationship used in this calculation is

$$C_D V^2 = \frac{mg}{\frac{1}{2}\rho A}$$

$C_D V^2 = 0.257\ \text{kg} \times 9.81\ \text{m/ s}^2 /(½ \times 1027 \times \pi \times (0.0239)^2)$
$C_D V^2 = 2.74$ (3.1)

Guess-1: Re=100.0 (Using the guess from the previous calculation)
Corresponding C_D=1.0
So from equation (3.1) V=1.65
Reynolds number=$\frac{\rho vd}{\mu}$=1027 (kg/m^3) ×1.65 (m/s) ×47.925 (mm) /1.4 (centipoises)=57856.77

Guess-2: Re=57856.77 (Using the guess from the previous calculation)
Corresponding C_D=0.6
So from equation (3.1) V=2.1
Reynolds number=$\frac{\rho vd}{\mu}$=1027 (kg/m^3)×2.1 (m/s) ×47.925 (mm) /1.4 (centipoises)=7.4876×10^4

It can be observed from the drag curve for spheres that there is very little change in drag coefficient due to change in Reynolds number in the range between 10^4-10^5. So the velocity of 2.1 m/s is the acceptable solution and shows little sensitivity towards any further change in Reynolds number.

(ii) <u>Considering cylinder</u>

This set of calculation will be done considering a cylinder facing the upward velocity

Corrections were made in this section as the dimension of cylinder length changed from 144 mm to 455 mm. Also the dimension d, which is supposed to represent a characteristic length required for Reynolds number is changed from 47.925 mm to 144 mm as the dimension 42.925 is the diameter of the equivalent sphere which is less of a characteristic length and the dimension 144 mm is the dimension of the hypotenuse of the rectangular cross section of the cylinder facing the flow and represents the

characteristic length more accurately. Corrections made by Kaushik Das on 1/11/07 and suggested by J Durham.

$$C_D V^2 = \frac{mg}{\frac{1}{2}\rho A}$$

$C_D V^2 = 0.257 \text{ kg} \times 9.81 \text{ m/ s}^2 /(\frac{1}{2} \times 1027 \times 445 \times 12.7 \times 10^{-6})$

$C_D V^2 = 0.85$ (3.2)

Guess-1: Re=100.0 (Using the guess from the previous calculation)

Corresponding C_D=1.0

So from equation (3.2) V=0.92 m/s

Reynolds number=$\frac{\rho vd}{\mu}$=1027 (kg/m^3) × 0.92 (m/s) ×144 (mm) /1.4 (centipoises)= 97183.54

Guess-2: Re=57660.8 (Using the guess from the previous calculation)

Corresponding C_D=1.5

So from equation (3.2) V=0.75

Reynolds number=$\frac{\rho vd}{\mu}$=1027 (kg/m^3)× 0.75 (m/s) ×144 (mm) /1.4 (centipoises)= 79225.7

Guess-3: Re=79225.7 (Using the guess from the previous calculation)

Corresponding C_D=1.1

So from equation (3.2) V= 0.87 m/s

Reynolds number=$\frac{\rho vd}{\mu}$=1027 (kg/m^3)×0.87 (m/s) ×144 (mm) /1.4 (centipoises)=92857.72

It can be seen from the curve that the value of C_D does not change much for a wide range of Reynolds number; hence an average velocity value of 0.9 m/s is considered.

Modified logic for determining the shear velocity at the cavity opening

Previously, a value of 0.2 was assigned as the ratio between the shear velocity and the critical velocity that is needed for lifting the nuclear material or the whole source assembly. But a closer look at some of the simulations and references show that this fraction is highly overestimated (about two orders of magnitude overestimation).

The following references were used to modify this fraction

(1) http://www.cfd-online.com/Wiki/Lid_driven_cavity_problem: This reference highlights a lid driven cavity flow simulation using the commercial software Fluent and shows the x-velocity distribution at different cavity locations
(2) Bouffanais, R, M.Deville, P. Fischer, E. Leriche and D. Weill, "Large eddy simulation of the lid-driven cubic cavity flow by the spectral element method", Journal of Scientific computing, pp 151-162, Volume 27(1-3) June 2006

Previously, it was assumed from the velocity profile that the x-velocity near the bottom of the cavity will be 0.2 times the velocity of shear at the opening of the cavity. There are two problems with this assumption

(a) We need an upward y velocity to lift the material from the cavity and considering the x-velocity will not give an accurate estimate
(b) The location of the source assembly will be in one corner of the cavity rather than at the middle of the cavity floor.
(c) The ratio 0.2 was overestimated as the actual cavity will be a deep cavity with L/D ratio less than 1.0
(d) The velocity at the bottom corner of the cavity will be considerably small and at those locations, the x and y velocity magnitudes are likely to be the same

It as estimated from reference 1 (simulation using Fluent) and reference 2 that the velocity magnitude of the cavity bottom corner and shear flow is about 100-200 or in other words the velocity discrepancy is about two orders of magnitude. Hence the estimated velocity magnitudes are listed below in the table for the whole source assembly. It should also be mentioned that the simulations and the reference talks about an L/D=1.0 cavity. In a deep cavity with L/D<1.0, the y-velocity magnitudes will be even less than what have been calculated for a square cavity.

Critical uplift (y-velocity) and the estimated shear velocity (at the opening) for the source assembly

Geometry and configuration	Critical Velocity	Estimated shear velocity (two orders of magnitude higher; i.e. 100-200 times the critical velocity)
Equivalent sphere diameter	2.1 m/s	210-420 m/s (469-939 mph)
Cylinder Diameter=12.7 mm Length 455 mm	0.9 m/s	90-180 m/s (201-402 mph)

All the estimated values of shear velocities are larger that that a natural event like tsunami or hurricane could produce on shore. This shows that the facility is safe from natural happenings like tsunami.

Corrections made here on 1/11/07 to reflect changes in dimension and velocity magnitude. Corrections made by Kaushik Das and Suggested by J Durham

Entry April 5, 2007

Contention related to Stylized fluid dynamics calculation

The Draft Topical Report's reliance on a "stylized fluid dynamic calculation" to assess tsunami impacts demonstrates a fundamental misunderstanding of a tsunami's terminal characteristics when it moves over land. Draft Topical Report at 3-4; see also Pararas-Carayannis Dec. ¶ 30. Over land, there is no structured wave form, but rather a chaotic turbulent water mass that admittedly would be unlikely to create wave velocities sufficient to pull a Co-60 source assembly out of the irradiator pool. Pararas-Carayannis Dec. ¶ 30. Because it misunderstands how tsunami affect coastlines, the Draft Topical Report fails to consider the most likely impact: flooding at the proposed irradiator site. Id. ¶ 31. The report does not evaluate the potentially severe consequences of tsunami-related flooding, such as the failure of peripheral equipment, power and back up generators, dispersal of leaking pool water, and grounded aircraft or equipment being carried and crushed against the irradiator facility, which could compromise the pool's integrity, draining the water below the minimum level needed to shield the Co-60 sources when the flood waters recede. Id.

Calculation for Flooding

Mass of the assembly m=257 gm
Volume=$5.7\text{x}10^{-5}$ m^3
Buoyancy force=$\rho\times g\times$Volume=$10^3\times5.7\times10^{-5}\times9.81$ N=0.565
P=Density of water

Weight of the assembly= m×g=$257\times10^{-3}\times9.81$=24.73 N

Weight/Buoyancy=43.76; So the object will never float

Typical drag force generated by tsunami=$C_D\times0.5\times\rho\times V^2\times$Area
Taking a typical result from the previous calculation Drag=10.19 N

Hence a larger force of drag was used in previous calculation compared to buoyancy.

Response

The fluid dynamic calculation assumes the worst case scenario where the tsunami wave directly impacts the irradiator pool. Subsequent breakdown of the wave structure to smaller eddies and coherent vortices will only have a fraction of energy of the original tsunami wave. Hence it is even less likely that this chaotic turbulent flow will cause the Co-60 source to be pulled out from the pool. The generated tsunami wave will result in flooding of the pool and the associated area, but the resulting buoyancy force due to accumulated water is about 2% of the weight of the source assembly and cannot displace it from the bottom of the pool. So the flooding due to tsunami will not cause the source to be displaced from the containment pool.